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- Geometric (match point) techniques for stereobathymetry, e.g., correlation.
- Density techniques to supplement the above stero/geometric algorithms


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This NORDA Technical note presents the results of the initial investigations on this project. The state of the art in digital photogrammetric bathymetry is reviewed and a relevant bibliography is included. Key issues involved in automated depth information extraction and identification/removal of environmental constraints are discussed.

Phase One tasks are presented: these activities include the development of a WPP Testbed and the evaluation/extension of appropriate algorithms to handle the key issues. Phase Two engineering considerations are also presented: these issues address the end-to-end engineering aspects of a total WPP System for coastal waters. Several appendices address various related topics: film properties, radiometry and geometry, further discussion of correlation algorithms, and spatial filterings.

NORDA Technical Note 186

Naval Ocean Research
and Development Activity
NSTL Station, Mississippi 39529

# Water Penetration Photogrammetry: Volume I, Feasibility and Evaluation Study

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- Geometric (match point) techniques for stereo-bathymetry, e.g., correlation.
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## ACKNOWLEDGMENTS

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# FEASIBILITY AND EVALUATION STUDY

## I. INTRODUCTION

The charting of near-shore bathymetry has been a long standing concern of the U.S. Navy as well as those organizations interested in the safety of international maritime navigation. The classic procedure for charting the bathymetry of the near-shore sea bottom has utilized surface craft and sounding lines. The ability to obtain information about sea-bottom topography was greatly speeded up in the last 30 years with the development of precision sonar equipment. However, these methods are inherently hazardous, time-consuming, and costly; given the existing hydrographic survey resources, it is estimated that thousands of ship-years will be required to acquire adequate worldwide hydrographic survey data (Hammack, 1977). Several hundred ship-years of work would be required to map--to modern standards--the near-shore or beach zone areas in which the Navy is interested (R. Brown, NORDA, pers. comm., 1982). Lundahl (1948) made note of the fact that maps or charts available before World War II provided little detail in beach zone areas; the reasons were the difficulty of performing hydrographic work in shoal water and the general lack of a need for detail in these nonnavigable waters. With the advent of World War II and the need to determine beach gradients for invasion forces, a number of solutions to the problem of determining underwater depth by aerial photography were proposed, tested, and found to be of varying worthiness. These techniques and their later refinement have proven the usefulness of aerial photography in hydrographic surveying. It appears that new or improved techniques using aerial photography offer one of the greatest potentials for satisfying the current requirements for more rapid and accurate techniques that can supplement or expedite the hydrographic charting process of near-shore coastal and shoaling areas.

Three primary techniques for determining water depth from aerial photography were investigated during World War II: the parallax method, the film density method, and wave methods (Lundahl, 1948). All these techniques have received further attention in later investigations. The wave methods (wave velocity, wave period, wave refraction) derive water depths through the analysis of wave patterns, which are known to react to water depths and sea-bed configuration, among other things. The wave methods, as originally formulated, had a number of drawbacks that argued against their use in an operational system. Seiwell (1949), however, argued that the wave methods showed the greater promise of practical development, but this has not been the case to date. The film density method attempts to correlate density with water depth. The method proved to be unreliable and was abandoned during the war. The method is akin to the multiband or multispectral photographic techniques for determining water depths that have been reported by other authors (e.g., Moore, 1947; Bailey, 1966; Hodder, 1971); but operational charting systems based on these techniques have not been developed. Also, bathymetry experiments with high gain multispectral (MSS) data from Landsat satellites have demonstrated the potential for supporting hydrographic surveying and charting efforts that would increase the safety of international maritime navigation (Hammack, 1977; Warne, 1978); but, again, operational systems have not been developed. While operational bathymetric analysis of the MSS data may come in time, it appears that if the major problems are to be overcome, it will be by an integrated approach utilizing satellite imagery, computer analysis, human interpretation, ground truth collection, and aerial photography (Warne, 1978). The most probable utility of the technique would be in expediting the update of inaccurate (old) charts for general navigation. The technique does not provide the scale or accuracy required by the DMA for charting near-shore bottom configuration, nor does it address the issue of using DMA's archived aerial photographs, which it wants to use in preparing these charts. At present, the accuracy requirements can be met only through the use of precision three-dimensional photogrammetric techniques that determine depths from parallax measurements of stereopairs of aerial photographs.

Modern color aerial photography, with its clear-water penetration characteristics and presentation of submerged detail, provides a tool for charting near-shore bathymetry through the use of precision three-dimensional photogrammetric techniques. Photogrammetric bathymetry is a two-media (atmosphere and water) problem that presents unique conditions not present in the normal (single media) photogrammetric case. Wave action and surf, water turbidity, two-media refraction, reduced optical transmissivity of the water, sun glitter, and the lack of optical contrast in underwater terrain impact the accurate interpretation and charting of underwater terrain from aerial photography. Still, photogrammetric techniques facilitate the charting of extensive areas and obviate the requirement for extensive on-site surveying with ocean-going vessels. Keller (1977) identified three potential benefits to be derived from photogrammetric bathymetry: improved accuracy and completeness of the hydrographic survey; reduced cost and time of the field hydrographic survey; and reduced ship requirements for a particular hydrographic survey.

DMA, recognizing the usefulness of advanced photogrammetric techniques, has tasked NORDA (Naval Ocean Research and Development Activity) to investigate their use for processing color photographs that are resident in their archives. In particular, because of limited (and expensive) facilities, and the large number of archived photographs to be processed, there is a need for more rapid and efficient automated charting techniques that eliminate the requirement for an instrument operator, or at least limits involvement to the resolution of those problems that are not readily handled by instrumentation.

Near-shore bathymetry has been successfully charted from photography with conventional analog stereoplotters (Tewinkel, 1963; Meijer, 1964; Losea, 1967; Rudder, 1972) and analytical plotters (Masry, 1975, 1980; Slama, 1980). Automated bathymetric charting has not been reported. Automatic stereo instruments measure parallax (and thereby terrain elevation) by electronic, optical, or digital means. The recent trend in mapping development has been toward the digital techniques, with advancements in computer technology and algorithm development having raised the possibility that visual-manual methods of information extraction from remote-sensor records may be replaced by more cost-effective automatic methods. Digital techniques provide flexibility in research and development as well as operational systems because they are not limited by instrument configuration--new processing techniques need only be implemented in computer software or firmware. While significant progress has been made in automating the processes of digital elevation extraction and orthorectification in the conventional case, these processes have not been developed for the underwater case.

This report addresses the problem of near-shore bathymetry via automated digital processing of archived/future color aerial photography, examines both the photometric and environmental restrictions, and proposes new areas of research/algorithm development which, when integrated with existing digital techniques, could lead to the development of a system for processing the DMA archived and future color aerial photography.

## II. BACKGROUND

Solution of the two-media photogrammetric problem requires procedures that depart from those used when light rays pass solely through the atmosphere. The degree of water penetration, lack of bottom contrast, refraction of imaging rays at the water-air interface, and incomplete stereomodels are among the problems that must be dealt with in charting bathymetry from aerial photography. Techniques have been developed that deal with many of these problems and thereby enable bathymetric charting to be done with analog and analytical stereoplotters, but there is no indication in the published literature of an attempt to solve these problems in the digital charting mode. Because the literature includes contributions from such government agencies as the U.S. Army Engineering Topographic Laboratories, the National Ocean Survey (NOS), the National Aeronautics and Space Administration (NASA), and the U.S. Geological Survey, the literature is judged to represent the state of the art in photogrammetric bathymetry; but this is not known with certainty because there is only indirect reference in the published literature to research, development, and production by the Navy.

It is important to note that in the reported cases of photobathymetric charting, project planning and the acquisition of aerial photography have been carried out with consideration for the problems specific to this two-media photogrammetric case. Because much of DMA's archived photography may not have been acquired with this problem in mind, it may be that this photography represents less than the optimal data set to be used for input to an automated bathymetric charting system. While system design (including data acquisition) should incorporate the experiences of previous investigations into this unique case of photogrammetric charting (a review of which is included in the following sections), previous experience also suggests techniques that may be applied to the problem of charting from existing photography.

### A. CONTROL AND TIDAL DATUM

The basic concern of photogrammetric bathymetry is to compile depth curves and spot elevations by relating points in the different coordinate systems of the underwater object system and the photographs in which this bathymetry is imaged. The relationships between these systems are determinable if object points whose positions are known in the object-space reference system (i.e., ground control points) are imaged in and positively identified in the photographs. Photogrammetric control points are generally classified as either horizontal (the horizontal object space position of the point is known with respect to the geographic parallels and the meridians or to other lines of reference) or vertical (the elevation of the point is known with respect to a vertical datum, usually mean sea level). The mean low water line (MLW) is the vertical datum to which water depths are referenced (Keller, 1975, 1977; Rosenshein et al., 1977). If photography is not obtained when the tide (land-water interface) is at the vertical reference datum, compiled elevation data can be reduced to the datum through the use of tide charts, if the date and time of photography is known. The problems associated with establishing photogrammetric control for nonbathymetric mapping are treated in standard texts (e.g., Wolf, 1974; ASP, 1980).

Single stereoscopic models can occasionally be oriented for the compilation of depth curves and soundings around small islands and inlets, but extensive offshore shoal areas require blocks of overlapping strips of aerial photographs to bridge the zones between vertical control points. In addition to points that are placed and targeted prior to aerial photography, more horizontal and vertical photo control points required for aerotriangulation need to be field surveyed after the aerial photography is obtained. The density and distribution of the ground control points are determined according to the requirements of aerotriangulation.

Control requirements for photogrammetric bathymetry are addressed in a number of papers by the staff of NOS (e.g., Brewer and Heywood, 1972; Harris and Umbach, 1972; Keller, 1975, 1977; and Slama, 1977) and are not dissimilar from the procedures used for nonbathymetric charting, except that some points may be either submerged or floating on water. Harris and Umbach (1972) argue against the use of surface floating vertical control because of the fake parallax introduced by a combination of horizontal and vertical motion between exposures, and because of the tendency of moored panels to dive into moving surf. Additional treatment of photogrammetric control for charting bathymetry and for using an inertial navigation system is given in Masry (1978, 1980) and MacPhee et al. (1982). To ensure the recovery of the location and attitude of the aerial camera on future missions, the Navy might consider procedures advocated by Masry (1980) and the use of a system such as the U.S. Air Force mapping and geodetic surveying airborne data acquisition system (Bernsden, 1972). The status of control for DMA's archived photography is unknown.

## B. FILM/PHOTOGRAPHY

To chart the sea bottom from aerial photography, it is necessary to "see" the bottom; that is, the sensitivity of the photographic film must be matched to the spectral transmittance of water. Considerable research has been done to identify the scattering qualities and spectral transmission of water and the best film/filter combination(s) to use for water depth penetration. Gordon and McCluney (1975) define the penetration depth of light in the sea--for remote sensing purposes--as the depth above which 90% of the diffusely reflected irradiance (excluding specular reflectance) originates. The degree of water penetration and image quality are functions of a number of factors, including the type of film/filter combination used, turbidity, sun angle, and the surface reflectance of the water.

The quality of an image is governed to a considerable degree by the optical properties of the water path. The various degradations introduced by the water path were identified in a paper by Mertens (1980). Wide-angle scattering of the illuminating light results in a loss of image contrast. This type of scattering is due in the main to suspended organic and inorganic particulate matter; but the contribution due to the water molecules is not insignificant, even in extremely clear ocean water. A loss of resolution is due, in the main, to narrow-angle forward scattering of light from the target. This type of scattering is produced by suspended particles and refractive inhomogeneities in the water. Very narrow-angle scattering is produced predominantly by relatively large suspended particles, which normally have indices of refraction comparatively close to that of sea water. A small fraction of the image-forming light, the "direct light" component, will pass through the water without interacting with the suspended particles. Under good conditions, image detail subtending less than one milliradian can be recorded even over long propagation paths. "Sufficient photons must be available in each resolution element in order to be able to record useful images. In many cases insufficient light will be the fundamental operating limit. Light in the blue-green wavelength region propagates best in most types of relatively clear water. The color selectivity of water is principally due to the characteristics of the water molecule. Most of the dissolved and suspended substances in sea water have little additional spectral effect. One exception is the so-called 'yellow substance,' which occurs frequently in coastal waters. It shifts the best propagation wavelengths toward the green region." (Mertens, 1980)

There is a lack of agreement in the published literature about the best choice of a film/filter combination for use in sea bottom charting. This is to be expected when it is understood that the recorded depth of penetration and image quality are dependent upon environmental conditions as well as the choice of a film/filter combination. There is no general agreement in the literature as to the maximum depth of penetration of light in water--and it may in fact vary over the area of a stereomodel. The maximum reported value is about 75 feet (e.g., Keller, 1975). Authors are in general agreement that specialized techniques are required to optimize the optical water depth penetration from aerial platforms; that the attenuation loss in water is as severe in the red region of the visible spectrum as in the deep blue, and absorption is very large in the infrared; and that general-purpose color films are superior to general-purpose black-and-white film in their ability to "see through" the air-water interface, although neither is optimized for water photography. A review of the literature pertaining to the evaluation of both experimental and commercially available films is given in Appendix A.

A determination of the optimum film/filter combination and photo mission parameters to be used for underwater charting could have a significant impact on future flight planning by the Navy. Because planning the aerial photography mission is vital to the successful completion of a photogrammetric mapmaking operation, it is instructive to ascertain the photographic acquisition practices of an agency actively involved in charting coastal waters. Such an agency is the NOS, which may be the biggest user of photogrammetric techniques for coastal mapping. A review of the literature pertaining to NOS practice is given in Appendix A.

The conclusions drawn from a review of the literature pertaining to the aerial photographic mission are summarized in this and succeeding paragraphs. Aerial photography for photogrammetric bathymetry should be obtained on a clear day after targeting of control and during (or very close to) mean low water, since bottom details are much clearer because of a shorter water-path. This specification restricts photography to those few times during the year when mean low water occurs during suitable sunlight conditions; that is, when the solar elevation angle is between approximately 20° and 30°. Unfortunately, this is the angle at which the upwelling atmospheric luminance that falls within the field of view of the sensing system is at its maximum. Because the atmospheric path luminance does not relate in any way to the luminance distribution of the ground feature, it has the effect of reducing the contrast of the image of the ground feature, e.g., the sea bottom (Slater, 1980). Egbert (1972) presented a method for determining spectral reflectance as a function of solar altitude, incidence look angle, and azimuth look angle, and demonstrated that the angular dependence of reflectivity can be used to optimize a target-background contrast ratio. The optimal solar altitude, incidence look angle, and azimuth look angle for achieving maximum illumination of the sea bottom, maximum image contrast, and minimal specular reflectance for photobathymetry have not been determined. While a determination of these parameters would have no bearing on the problem of mapping from existing photography, they would provide an aid to planning future missions.

Overlap of photography should be between 70% and 80% (normal is 60%) both along and between flight lines to combat the problem of sun reflection from the surface of the water and to meet aerotriangulation needs. Two-media photogrammetry does not impose any special restrictions on photo scale. As in the conventional case, this is dictated by accuracy requirements and constraints of compilation instrumentation. Harris and Umbach (1972) recommend a flying height at least 100 times as great as the depth of water to be charted so as to minimize the errors in refraction compensated image coordinates. Since there is no significant difference in the metric stability between color and panchromatic film systems (Umbach, 1968), the film type providing the greater depth penetration and bottom contrast should be used. The preferred film/filter combination is Kodak Ektachrome EF Aerographic type SO-397, with a Wratten No. 3 filter for haze reduction. Black-and-white infrared film may be used to delineate the land-water interface when sufficient vertical control cannot be established.

If digital correlation is to be the basis of compilation, the use of color infrared (green, red, and infrared sensitive) film alone might be considered. A digital separation of the green and infrared sensitive dyes would produce one image (green) to be used in correlation and one image (infrared) to help as vertical control for leveling. In the instance of archived color photography, two digital images (blue and green) can be used in correlation and one image from the red sensitive emulsion may help as vertical control for leveling. The ideal film for digital photogrammetric bathymetry would seem to be the one which combines the blue and green sensitive emulsions from color film and the infrared sensitive emulsion from false-color infrared film. In its long-range planning, consideration might be given to the development and testing of an experimental film with these sensitivities.

## C. AEROTRIANGULATION

The problem of obtaining sufficient vertical control for leveling stereoscopic models is solved by two-media aerotriangulation. Aerotriangulation, aerial triangulation, or phototriangulation is the process of extending the horizontal and/or vertical control required for photo mapping by relating measurements of angles and/or distances on overlapping photographs using the perspective principles of the photographs. Aerotriangulation methods are extensively documented in the photorammetric literature, e.g. in Wolf (1974), ASP (1980), and Ayeni (1980), and considerations specific to two-media aerotriangulation are treated, for example, in Harris and Umbach (1972), Brewer and Heywood (1972), ASP (1975), Slama (1977), Masry (1970), and Masry and McRitchie (1980). In aerotriangulation, the effect of refraction at the water-air interface must be taken into account for underwater imaged points. To be theoretically correct, formulation of the mathematical model for two-media photogrammetric triangulation must be based on the actual underwater point rather than its refracted, or apparent, position. The corrections to be applied to measured image coordinates are determinable given the index of refraction, nominal flying height, and water depth at the time of photography. Following coordinate refinement for comparator error and film and lens distortion, the refraction-compensated coordinates of vertical control points can be determined prior to aerotriangulation using the equations given in the section "Geometric Correction," Appendix B. Harris and Umbach (1972) advocate that the unknown depth of photogrammetric pass points to be solved as an additional unknown in an iterative analytical block aerotriangulation.

The use of the block adjustment method in aerotriangulation reduces the volume of ground control survey work, provides the greatest accuracy, and is the preferred method of control extension to be used with the DMA's photography. While the method may be readily used with test range photography, it is most likely that the method cannot be used with much of DMA's archived photography because of the prohibitions against field survey work, and other methods would have to be used in those instances. If control is insufficient for leveling and referencing models, then techniques using the water surface or shoreline as a reference datum for leveling may be possible in some instances. Masry (1980) presents a treatment for obtaining relative orientation and leveling of incomplete stereomodels using the water surface as a vertical reference. The water surface is determined from simultaneous photography from two aircraft as suggested by Tewinkle (1963). In those instances of uncontrolled beach photography where a control survey cannot be conducted because access is denied, these areas might be charted to less than desired standards by the method suggested by Berry and Rudder (1972).

Aerotriangulation software is supported by federal agencies (e.g., USGS, DMA, ETL, NOS) involved in mapping and charting from aerial photography; NOS is known to have aerotriangulation software modified to handle the two-media problem. Given adequate control and camera calibration, this software would be appropriate for use with DMA's archived photography. Within federal agencies, existing block aerotriangulation software packages use conventional comparator measurements of fiducials, pass points, and control from frame photographs. The U.S. Army Topographic Engineering Laboratory has the capability of obtaining these measurements with their PDS 1050A microdensitometer with comparator capability (Crombie and Ackerman, Photogrammetric Engineering and Remote Sensing, Sept. 1976). It is likely that the requirement for a comparator can be eliminated in a fully automated digital system. Wolf and Keating (1970) have developed a technique for performing aerotriangulation utilizing digital correlation of image densities. If digital aerotriangulation were to be adopted as a procedure within an automated charting system, instrumentation requirements could be reduced to a scanner for analog-to-digital image conversion and computer hardware.

## D. INSTRUMENTATION

Two distinct areas are included within the definition of photogrammetry: interpretive and metric. Interpretive photogrammetry--photographic interpretation and remote sensing--involves the systematic study of remove sensor records, e.g., photographs, for the purposes of identifying objects and of judging their significance. Metric photogrammetry involves precise measurements and computations to determine sizes and shapes of objects. Both metric and interpretive photogrammetry are components of any mapping/charting system that uses aerial photography as the principal source of information. An automated digital photogrammetric system requires the use of a computer for both the interpretive and the metric functions. In this instance, numerical image correlation (match point definition) constitutes the interpretive function, and metric information about the interpreted image points is related to positions in the object world through analytical methods.

Processing of photographic image data, notably an implementation based on electronic digital computers, e.g., digital correlation, dictates that images must be converted from continuous to discrete form. A digital image representation is usually accomplished by sampling the photographic image at a discrete number of points in the x-y plane and storing the sample value; that is, the image is discretized both in spatial coordinates and in brightness. This process is called sampling or quantization. The problem of spatial quantization has been solved, almost universally, by sampling the image at a discrete, regularly spaced set of points, the samples being quantized to a set of equally spaced gray level values. Such a set of samples can be represented, for computer-processing purposes, as a rectangular array whose row and column indices identify a point in the image, and the corresponding array element value identifies the gray level (brightness) at that point.

The conversion of a photographic image into a numerical representation suitable for input to a digital computer is most commonly achieved with an instrument called a microdensitometer. The device requires that the image to be digitized be in the form of a transparency, e.g., a film positive. The transparency is mounted on a flat bed or wrapped around a drum and translated relative to a beam of light which, after passing through the transparency, is focused on a photodetector. The intensity of the beam is sampled and, by means of an analog-to-digital converter, discrete values or intensity are obtained and written on a mass storage device. With color a consideration, multiple scans of the transparency are required--one scan for each of the light sensitive film layers.

Microdensitometers are not the only systems available for rapidly converting photographs into the proper digital data form. Montuori (1980) evaluated image scanning technologies--electronic, electro-optical, and solid-state--with respect to requirement for digital mapping systems. These requirements depend upon the specific uses intended for the digital output as well as the environment (production, research, and development) in which the scanning will be used, and whether it will be used on-line, interactively, or off-line. The trade-offs include speed, degree of automation, flexibility, cost, resolution, and accuracy (both geometric and photometric). When the trade-offs are evaluated with reference to the environment in which the scanner will be used, it becomes clear that no one system can satisfy all operational requirements. When evaluated against the performance criteria of format accommodation, resolution, data rates, geometric and photometric accuracy, and dynamic range, Montuori concluded that the systems adaptable to all these requirements include drum type, laser scanners, rotating-mirror laser scanners, and solid-state scanners comprised of a series of optically butted linear arrays. Experience at the University of Wisconsin (Janssen, 1979; Townsend, 1981) indicates that drum type microdensitometers can require calibration to achieve the required geometric accuracy. The flat-bed microdensitometer meets or exceeds all requirements except data rate. If cost is not a constant, any of these scanner types would be suitable in an off-line research and development environment. The selection of a scanner for a production environment is a more difficult question. Production requirements will depend on the decision as to whether correlation will be performed in an interactive or off-line mode, correlation rates, accuracy requirements, and a host of other variables. Scanning requirements for an operational digital photogrammetric mapping system will become more apparent as research on the other components of this system progresses. The scanning technology needs to be evaluated and ranked in light of the requirements of a total production system design; therefore, an evaluation of scanning technology should be initiated as specifications for other system components are hardened.

Automation in photogrammetric instruments, extending from computer control of analog stereoplotters through fully automated correlation equipment, has necessitated process specific hardware components and software. The state of the art in automation of photogrammetric processes has been thoroughly documented elsewhere (e.g., Case, 1980; Mackarovic, 1980; Konecny, 1981) and is not repeated here. A review of this literature and Opitz (1982) indicates that the development trend is from analog to digital techniques, and in the latter case, the epipolar geometry* and the use of digital image processing is gaining in importance. This trend will reduce the dependence on special hardware. A requirement for special hardware is dependent on the level of automation; that is, the degree to which an operator is required to interact and control processes, and the choice between an on-line or off-line system. Makarovic (1980) identifies the main properties of on-line and off-line systems, which are repeated here:

*An epipolar line is defined by the intersection of an epipolar plane and each photograph of a stereopair. An epipolar plane is any plane passing through the perspective centers of the two photos of a stereopair.

| ON-LINE SYSTEMS | OFF-LINE SYSTEMS |
|---|---|
| • Time constrained operation--with real time outputs (final).<br>• Complex dedicated equipment.<br>• Great data throughput.<br>• Limited versatility (i.e., diversity of inputs and outputs).<br>• Limited flexibility (strategies, mathematical models).<br>• Operator support in failure states. | • Time delayed operation with intermediate recording/retrieval of large data sets.<br>• Minimum of dedicated equipment<br>• Phased but parallel operations<br>• Throughput depending on the equipment.<br>• Great versatility (type and structure of inputs and outputs.<br>• Great flexibility (strategies, mathematical model. |

Examples of automated instruments that perform on-line digital image correlation along epipolar lines are the Gestalt Photomapper (Kelly et al., (1977) and the Bendix AS-11B-X (Scarano and Brumm, 1976). These instruments are capable of producing digital terrain models (DTM) with on-line digital techniques--their use for producing water depths has not been reported. A principal advantage of on-line correlation is that an operator can intervene when correlation fails. The generation of DBM's with off-line digital techniques using software and parallel processors for the correlation of previously scanned and recorded imagery was demonstrated by Panton (1978), but an operational system based on this work has not been reported. Panton's work was done under contract to the U.S. Army Topographic Engineer Laboratories (ETL). Software development for topographic applications continued at ETL and has been reported on by Norvelle (1981, see Appendix C). An on-line, interactive system is particularly suitable for testing various pre-processed data. If production work is to be done at the Defense Mapping Agency Aerospace Center, it is preferable that the system design be compatible with DMA's Integrated Photogrammetric Instrument Network (IPIN), at least for editing.

A procedure for the automatic off-line generation of digital terrain models has been proposed by Makarovic (1980). An off-line method is characterized by a minimum of dedicated equipment and flexibility with regard to the matching algorithms. Because the cost of computers and memory are decreasing rapidly relative to specialized hardware, it is expected that off-line correlation will likely become competitive with respect to cost, accuracy, and reliability requirements. "This will happen when mass storage becomes inexpensive enough to store the total information from the photos" (Konecny, 1980). It is now possible that large amounts of real memory can be installed in general purpose mini- and micro-computers. This offers exciting possibilities for the design of prototype and production systems that only involve software development. If large segments of a stereo model can be loaded into the memory of a computer at one time, then efficient search/correlation algorithms can be implemented. Sixteen megabytes of real memory would be adequate for color channels in each of two photographs of 1.5K * 1.5K pixels. A minicomputer such as the VAX-11/780 could serve as a prototype host computer. Ultimately, a less expensive alternative such as a microcomputer based on a Motorola 68000 might be sufficient. These innovative design considerations should be addressed in the next phase of this project.

As in the case of scanning technology, the computer hardware/firmware/software requirements for a research and development environment for evaluating digital photogrammetric processes can be satisfied by a variety of configurations; but the requirements for a production system cannot be specified yet. The hardware requirements for a production system should be evaluated as part of the systems analysis, which includes an evaluation of scanning technology.

## E. COMPILATION/CORRELATION

The first attempts to use the conventional methods of height determination from parallax measurements of stereopairs of aerial photographs to chart water depths appear to have been made during World War II (Lundahl, 1948). Early attempts were abandoned because height determinations could not be made within one or two feet of their correct heights and because the floating dot in parallax equations could not be accurately placed in the small-scale photography used, due to the loss of beach texture. The problem was eventually solved with large-scale (1:500), continuous strip stereophotography obtained with the Sonne Camera. Bottom detail was found to be necessary to provide reference for measurement; it was essential to have ripples or slight waves on the water to record the surface image on the film. The Sonne Stereo Comparator was used to measure the distance between the surface of the water and the bottom. Average errors of less than one foot, which was considered sufficient for predicting how landing craft would ground, were achieved with Sonne photography. Solodovnikova (1962) reported the compilation of spot depths from panchromatic film and Tewinkle (1963), Meijer (1964), and Loseva (1967) have since demonstrated the analog technique for compiling depth curves and spot elevations from color photography. Harris and Rudder (1972) reported the NOS's advancement of the analog technique to an operational level. Masry (1975, 1980) and Slama (1980) have reported the use of analytical plotters to compile depth data. In all instances the interpretive phase, i.e., point selection, has been performed by an instrument operator using color diapositives. Rudder and Berry (1972) concluded that positive transparencies were better than negatives for the efficient interpretation of underwater detail.

The compilation of underwater digital terrain models with automated digital instruments has not been reported. If an automated digital system is to be used, both the interpretive and metric aspects of the photogrammetric bathymetry problem will be performed by computers. Numerical methods would be used in this instance both to identify and locate corresponding imagery on two overlapping photographs and to compute the depth of points. In digital approaches to image matching, the parallax used in photogrammetric formula for computing height/depth is a product of the matching process.

In a digital photogrammetric system, images are represented by arrays of integer film density values. (A single [B&W] channel of data for digital correlation is typically derived from diapositives. Lindig (1980) tried to determine whether negatives could be more favorably used than diapositives, with mixed results: the number of correlation failures was higher and inversely proportional to accuracy. An attempt to exploit the additional information in color film has not been identified.) To find corresponding imagery, arrays from the left and right photos are compared numerically through the use of formulas known as density difference algorithms, i.e., correlation algorithms. Numerous techniques for computing the correlation function are well known and are given, for example, in Helava (1978), Makarovic (1980), Konecny (1981), and Norvelle (1981). It appears that the issue of multi-channel correlation has not been investigated, most certainly not for the underwater case.

The normalized cross-correlation algorithm appears to be the one most commonly used because it tends to account for differences in the brightness of the "target" (left photo) and "search" (right photo) arrays due to such factors as lens fall-off, photo processing, unequal exposure time, and differences in viewing angle by subtracting average densities from the target and search arrays. Other simpler, more time-efficient algorithms can be used provided they meet the accuracy and reliability requirements.

Regardless of the correlation algorithm chosen, however, one of the most critical problems concerning digital correlation has been the heavy computational load. Image shaping and the epipolar geometry have been exploited in structuring the search process in correlation so as to minimize the number of matching trials and improve the predictive selection of points. Knowing the relative orientation parameters and coordinates of the perspective centers for a stereomodel makes it possible to exploit the epipolar geometry and thereby greatly reduce the size of the search area and, consequently, the number of correlation coefficients that must be computed. This is so because, when epipolar scanning is used, only one-dimensional data shaping and searching are necessary and, by memorizing the preceding profile, the one-dimensional data shaping and searching are necessary and, by memorizing the preceding profile, the one-dimensional search can be limited to a very small range. Helava (1978) states that exploitation of the epipolar geometry reduces the computational requirements by approximately an order of magnitude. Additional reduction in the computational load has been realized by minimizing data administration and arithmetical operations, by structuring the image data, and by removal of redundant image data.

Two problems associated with correlation concern the reliability and accuracy of correlation. The influencing factors identified by Makarovic (1980) are as follows:

RELIABILITY

- Quality of image data
- Data structure
- Prediction of conjugacy
- Mathematical model(s)
- Image dissemilarity
- Adaptive operations
- Search routines

ACCURACY

- Quality of image data (high frequency band)
- Data specifications (sampling)
- Mathematical model(s)
- Image dissemilarity
- Adaptive operations

These factors, with the exception of image quality and image dissimilarity, are dependent on the effectiveness of algorithm development and are treated by Makarovic (1980). There has been little treatment in the literature of the image quality and dissimilarity factors in correlation, which originate in the varying light reflectance, times of exposure, lens fall-off, artifacts, and spectral properties of the film. The image quality and dissimilarity factors are perhaps the last resolved problems in digital stereomapping and are therefore the most significant problems affecting the reliability of image matching. These problems could be mitigated to some extent by judiciously planning the aerial survey mission and by preprocessing the image data.

Image correlation in photogrammetry is a topic that has received considerable attention. The literature on this topic is voluminous, and only a cursory review of the problem has been presented here. Suffice it to say that, although further investigation is necessary, the technology has advanced to the point where it may be reasonably considered for charting near-shore water depths. The state of image correlation development in photogrammetry is perhaps best summarized by quoting from Makarovic (1980):

> The development related to image correlation in photogrammetry has been fragmentary, and is characterized by increasing complexity and diversity of the methods and means. Hence, there is a need for an orderly approach to the problem area as a whole.
>
> The recent development trend has been from analogue to digital techniques, and in the latter case the epipolar geometry has gained in importance. The use of epipolar geometry is effective in image matching, though it may cause some distortions in orthophotographs if produced on-line.
>
> When developing a new automatic system with the image matching capability incorporated, it should be optimized as a whole, including the input data. A fundamental, but often insufficiently considered principle is to balance the complexity and sophistication of the algorithms against the quality of the input data.
>
> In general, the performance and reliability of image matching can be improved by specifying rationally the input and the process parameters, by intelligent conditioning of the image data by implementing an effective matching strategy, and by a well devised interactive man-machine operation.

## F. ACCURACY REQUIREMENTS

The accuracy requirements of NOS are given in Keller (1977): depths of less than 11 fathoms (approximate maximum depth for photobathymetry) are to be measured to within one-half foot and greater depths to within 1%, unless specifically authorized. These requirements may be lowered to one foot for depths less than 11 fathoms and 2% in greater depths in rapidly changing depths and over irregular bottom. The U.S. Navy accuracy standards are embodied in the IHO (1968) standards, which specify that depths of 20 meters or less are to be measured to within 0.3 meter. These standards are consistent with the one-foot accuracy requirement, which Lundahl (1948) stated was required for predicting how landing craft will ground. Keller (1977) reports that in a production mode, analog stereoplotter operators achieve 0.5 foot accuracy for 90% of the vertical readings in a 1:10,000 scale stereomodel; point accuracy after correction for office-established vertical control is about ±1.2 feet. Since analytical instruments are, in general, more accurate than analog instruments, it is expected that this condition would hold in the bathymetric charting case. But few results have been reported. Masry (1975) has reported an RMS error of less than one-half meter for test models with depth measurement by analytical plotter when compared to sounding measurements.

## III. AUTOMATED DEPTH EXTRACTION FROM COLOR STEREOPHOTOGRAPHY

The advanced development effort being carried out by the NORDA Pattern Analysis Branch under this Water Penetration Photogrammetry (WPP) Subtask is planned to investigate the following areas:

(a) Geometric (match point) techniques for stereobathymetry; e.g., correlation.
(b) Density techniques to supplement the above stereo/geometric algorithms.
(c) Automated identification and removal (where possible) of environmental artifacts and constraints in the imagery.
(d) Use of image enhancement as an aid to the above items and for generating digitally improved photographs for conventional stereo compilations.

The proceeding Sections have provided background information for these tasks; this Section will consider key issues related to items (a), (b), and (d) above; the next Section will present a discussion of environmental problems associated with automated depth information extraction.

Before proceeding with further discussions of these topics, however, it should be noted that several areas reviewed in the previous Section will not be considered under the First Phases of this Subtask. DMA (Hammack) has indicated that solutions to the aerotriangulation and control/tidal datum problems have already been developed for semi-automated approaches to stereo compilation (e.g., the MUSAT programs). Furthermore, detailed consideration of film/filter combinations, mission planning, etc., will not be covered initially. These items, along with an end-to-end design for a totally automated system, may proceed in Phase Two of this Subtask after completion of the advanced development efforts required to investigate/extend the necessary algorithms for automated depth extraction from the stereo photography and techniques for properly handling the environmental problems.

Automated depth (bathymetric) information extraction from stereophotography can be divided into two basic categories:

(a) geometric techniques based on triangulation and the identification of common points in both photographs.

(b) density techniques based on concepts that relate water depth to radiometric intensity (light attenuation as a function of the length of the water column).

As presented in the previous Section, the use of stereophotography for mapping has a long and significant history. Automatic techniques are used for some types of topography (digital terrain elevations or DTMs) by DMA and others. Extensive use of color stereoimagery is made by Naval Ocean Suvey (NOS) for near-shore bathymetric data generation with analog and analytic stereoplotters. These stereo/geometric techniques rely on the identification of the "same object" in each of two (or several) photographs taken under known (controlled) geometric position and orientation conditions. The fully automated techniques used over land, such as the topographic use of the DMA ACE, identify these common points (or match points) by correlation techniques on specialized hardware. The various stereoplotters require human operators to make this identification/decision. As indicated earlier, no fully automated operational stereo system for the bathymetric problem has been reported in the literature. Thus one of the major thrusts of the current Subtask is to extend the geometric (stereo) techniques to develop fully automated prototype algorithms for application to DMA's near-shore bathymetry problem.

The second class of automated bathymetric techniques, depth extraction solely from radiometric measures of water column absorption, are still in their exploratory phase. Considerable efforts have been expended on this topic, particularly as related to the exploitation of satellite data; notable examples of such work are the ERIM studies. (Lyzenga) The density techniques considered under this Subtask will take advantage of developments in both of the above areas. Since stereo/geometric information is available over at least some regions of the photographs, this depth data can be used to calibrate the density patterns. Therefore, the requirement for absolute radiometry and the corresponding complex models of absorption and environmental parameters necessary for satellite remote sensing treatment of bathymetry may be avoided. However, the basic concepts that are employed for the satellite case, the relation of film density to water column length (absorption), can be applied in a relative way to interpolate across regions in the photograph for which match points cannot be determined or to lessen the computational load imposed by such calculations.

Finally, a wide literature and "algorithm library" dealing with image enhancement/ restoration is available. This Subtask will explore the utilization of such techniques to improve the stereo/geometric match point identification procedures. For example, it is well known that correlation algorithms have particular difficulty in regions of low contrast (Panton, 1978). There is a large number of digital image processing techniques, however, that are specifically designed to improve such contrast problems. Figure 1 shows such an example. Application of such digital (softcopy) enhancement procedures, both for automated depth extraction as well as photo interpretation (stereoplotters), have received limited attention. Because the other issues addressed by this Subtask will require computer image processing techniques in a fundamental way at various stages of the depth extraction process, these studies can easily be extended to included/evaluate softcopy photograph enhancement (with film writing for the stereoplotter case). In particular,

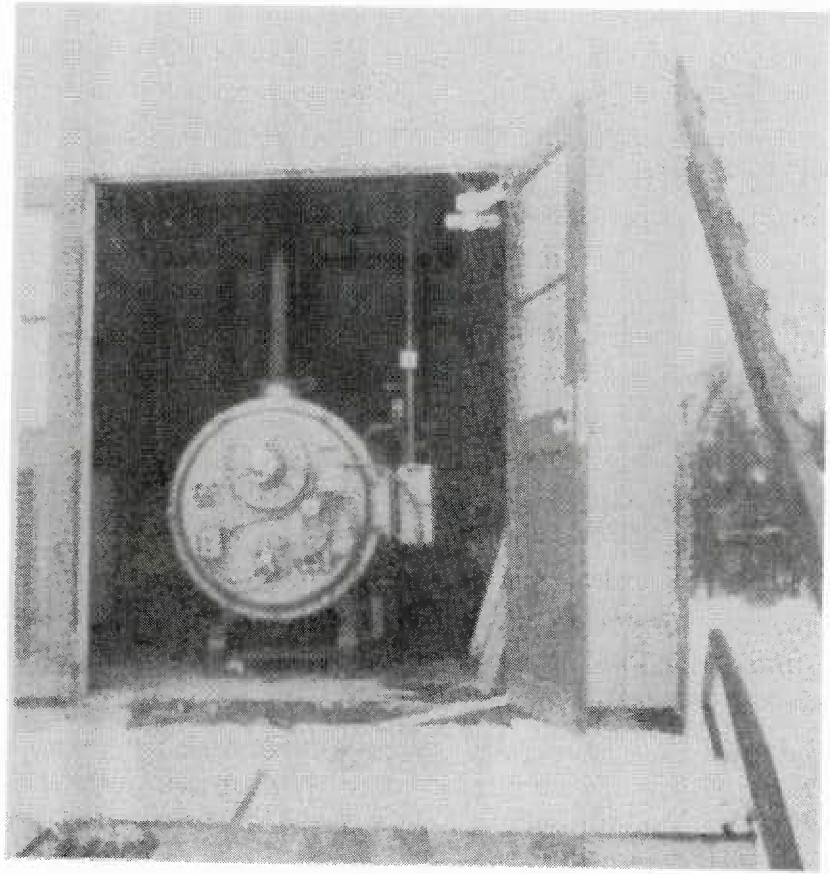

Figure 1A. Example of image enhancement
(original image)

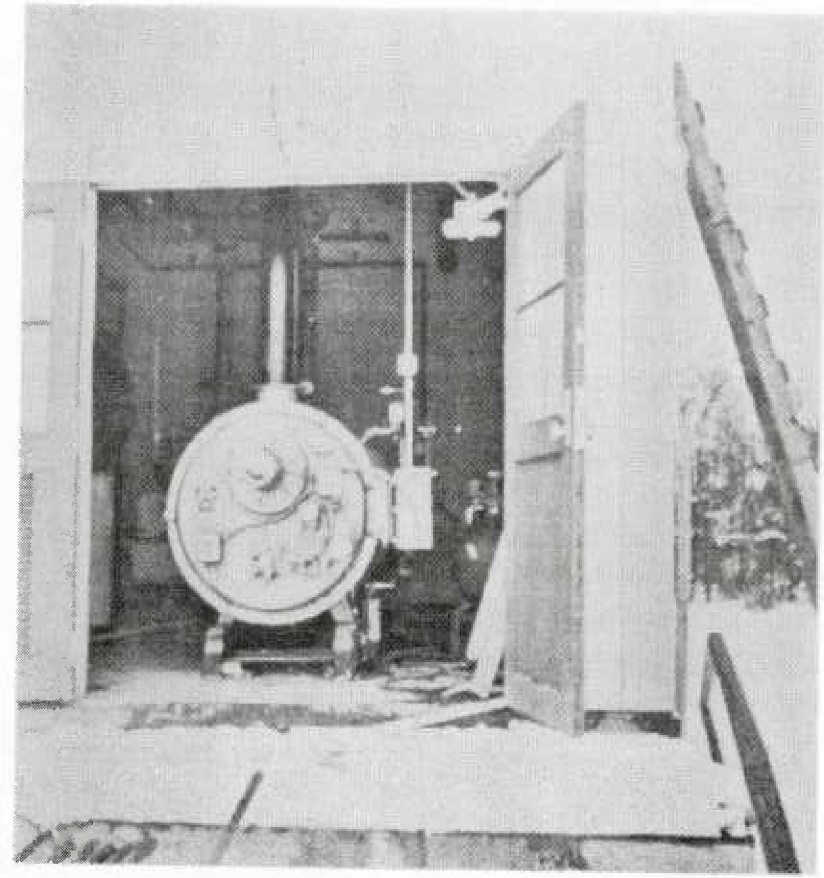

Figure 1B. Example of image enhancement
(contrast enhanced image)

the effect of such preprocessing on correlation techniques will receive considerable attention.

As indicated in the previous Section, two key problems in the use of correlation for match point identification are accuracy and reliablity. What the determining factors are that affect these two items in the shallow water environment needs to be considered. It is well known that examination of the various statistical measures generated by the correlation process does not provide assurance or information as to whether the correlation has indeed found true geometric match points (in contrast of points with a "high correlation value"). In this sense correlation is not a fail safe procedure. In fact the images must exhibit sufficient differences (i.e., parallax) in order to use stereo/geometric techniques for depth determination. It is well known that successful application of correlation procedures to aerial land photography depends greatly on the scene in question; it is sometimes even necessary to simply try the correlation procedure in order to determine if it will work. High contrast urban scenes, for example, usually confuse the correlator where as certain kinds of mountainous areas are handled quite well. Such comparisions with land imagery lead one to investigate the nature of correlation and the parameters which effect it for near-shore bathymetry. Issues which need to be addressed in this regard involve image pattern structure, seafloor gradients, spatial frequency content, contrast, intensity levels, and spectral (color) characteristic.

Another key issue concerns proper exploitation of the color nature of the photography. Three automated correlation approaches to land photography were reviewed briefly by NORDA during FY82: the ACE at DMAAC, the Gestalt Photomapper at Toronto, and the Digital Interactive Mapping Program (DIMP) at ETL. All three systems require monochrome imagery. Preliminary trials were made on each system using a color image of the Cat Cay Island area in the Bahamas. This photograph was reduced to a monochromatic image either by the inherent nature of the system or by digitizing only one color channel. This initial work raised the question "Do the color bands contain additional information which could improve correlation, and, if so, how should one incorporate such multi(spectral) channel data in the correlation process?" Furthermore, as will be discussed more fully in the next Section, the multi-band information in color photographs is probably critical to identification of environmental problems. Color and shape based pattern analysis recognition techniques might be used to identify scene content that is related to environmental contamination. Stereo photographs can be digitized in several bands which create separate spectral images of the seafloor. One can then use various combinations of these images (e.g., band ratioed images, various weighted sums, etc.) as input to a "monochrome correlator." One could also extend the single valued (scalar) pixel-by-pixel correlation by using multivalued (vector) correlation techniques. The applicability of these procedures for automatic depth information extraction needs further investigation.

In addition to extending the correlation concepts through the use of multivalued pixels, one can also extend it to include other sorts of "derived images." Thus, one can employ a variety of different image operators before performing correlation. The use of filtering in this application (e.g., Ehlers, 1982), of course, is well known; a variety of other intensity modification techniques can also be employed; for example, contrast stretching, various intensity equalization schemes, edge enhancement, etc. Continuing this line of reasoning, one might include images containing the results of edge detection algorithms;* i.e., binary line images based on various edge detection techniques (explored, for example, by the DMA Digital Pilot Operations Program). Thus, one might consider a spectrum of stereo/geometric match point algorithms ranging from simple pixel-by-pixel single-valued correlation (DMA ACE) through various enhancement and/or multispectral image techniques to complex symbolic scene matching based on image content identification. DMA is familiar with (and has supported) this complete range through its previous development programs. A few appropriate techniques from this range of approaches will be selected for consideration under this Subtask.

The effect of various distortions or image degredation also needs to be considered. It may be necessary to make geometric corrections to the stereophotography. These pixel-by-pixel image corrections might improve the match point determination process by removing shape distortions. Geometric errors in image point positions in single media photogrammetry (atmospheric refraction, earth curvature, lens distortion, film shrinkage/expansion, comparator) are well known and documented in standard texts (e.g., Wolf, 1974; ASP, 1980). In a two-media photogrammetric problem, one must also account for the additional positional error introduced by refraction at the water-air interface. Such individual picture point corrections are in addition to those that are necessary to calculate true depth from the apparent depth as obtained from the parallax measurements at spot elevations or contours.** The extent to which

*Fainitch (1980) alluded to the use of a number of Laplacian enhanced and edge only enhanced images to support various types of electro-optical correlation systems.

**Various computer programs which implement the "height" calculations have incorporated algorithms to deal with this refraction phenomenon in the depth calculations by correcting apparent depth (uncorrected parallax) to true depths. A mathematical model (based on the work of Rinner (1969) for treating the photograph image coordinates for the effect of two-media refraction on known underwater points (e.g., control points) is given by Harris and Umbach (1972) (see Appendix B).

these geometric distortion in the stereophotography affects the match point determination algorithms may require investigation. One might note, however, that these image distortions apparently do not affect compilation on conventional stereo-plottor instruments. Furthermore, some correlation schemes deliberately perform "window shaping" or "distortion" of one image patch to the corresponding search region in the reference image (see Norvelle, for example). Such "shaping" either removes or introduces "proper distortions" between the images in order to improve the correlation match. How these two geometric problems interact is not clear at present.

Radiometric calibration and/or corrections may also be necessary for automated depth extraction from stereo color photography of near shore areas. It is true that both the geometric and the density technique (as planned for use in the WPP Subtask) are based on relative intensity data. In the stereo/geometric case using symbolic matching, intensity distortions affect only the ability to "recognize the same object" in both stereo pairs. If this determination is primarily shape dependent, then intensity distortions may not be important. At the other end of the match point techniques spectrum where a simple absolute difference of pixel values is used, it is clear that the radiometric distortion of lens fall-off will affect the correlation results. Lens fall-off will also affect relative density techniques when one interpolates into the vignetted areas because of an artificial change in film density which is not related to water column length. A further discussion of the radiometric problem in general is presented in Appendix B.

## IV. ENVIRONMENTAL CONSTRAINTS

The application of automated depth determination algorithms, either automatic match point (geometric) techniques such as correlation or density interpolation techniques, will be affected by the environmental conditions appearing (photographed) in the imagery. Correlation will not be possible when the bottom detail is obscured by the sun's reflection in the sea surface, wind-produced surface ripples, turbidity of the water column, bottom type/homogeneity or cloud shadows. The following four sections address the various categories of environmental artifacts and constraints and discuss briefly the applicability of potential image enhancement/feature recognition schemes for dealing with these environmental conditions.

### A. SUNGLINT/SURFACE REFLECTANCE

To obtain depths from aerial photography one must, of course, "see" the sea floor. Two environmenal effects at the sea surface restrict such seafloor viewing: sunglint and sea surface reflectance. These effects are illustrated in the color aerial photograph over Cat Cay in the Bahama Islands (Fig. 2) at the regions marked "A" and "B", respectively. In the lower left corner (sunglint area), it is evident that the detail of the bottom features is lost as one approaches intense reflection at the solar specular point (SSP). On the outer periphery of the SSP the bottom features are just observable, underlying the surface reflections.

Clearly, any determination of water depth cannot be done in the solar specular region. It is desirable, however, for the depth measurement to be made as far into the sunglint area as possible without the loss of bathymetric accuracy. As the sea surface roughness changes, certain slopes or facets of the sea surface are oriented to mirror the sun's reflection. On these isolated wave surfaces, high solar reflectance occurs, although not to the extent that is observed at the solar specular point. The same physical reflection is occurring as at the sunglint point, although it is termed surface reflectance when applied over wave roughened surfaces. An example of surface reflectance is illustrated in Figure 2 (Annotation B). Notice that this area is well out of the sunglint area, yet upon close examination, high reflection off the surface waves occurs in a regular pattern. The pattern of this glitter is aligned with the surface wave directions and degrades the resolution so that one is unable to detect bottom features. In this photograph, the sea surface roughness is minimal and is influenced by a predominant wave direction and period. However, in very rough, confused sea states, the sea surface reflectance can increase substantially. Since surface reflectance occurs in all areas of the visible spectrum, all the imagery received by the camera is contaminated to a certain degree by this noise. Thus, it can be demonstrated that for certain sun altitudes, camera-viewing angles and surface

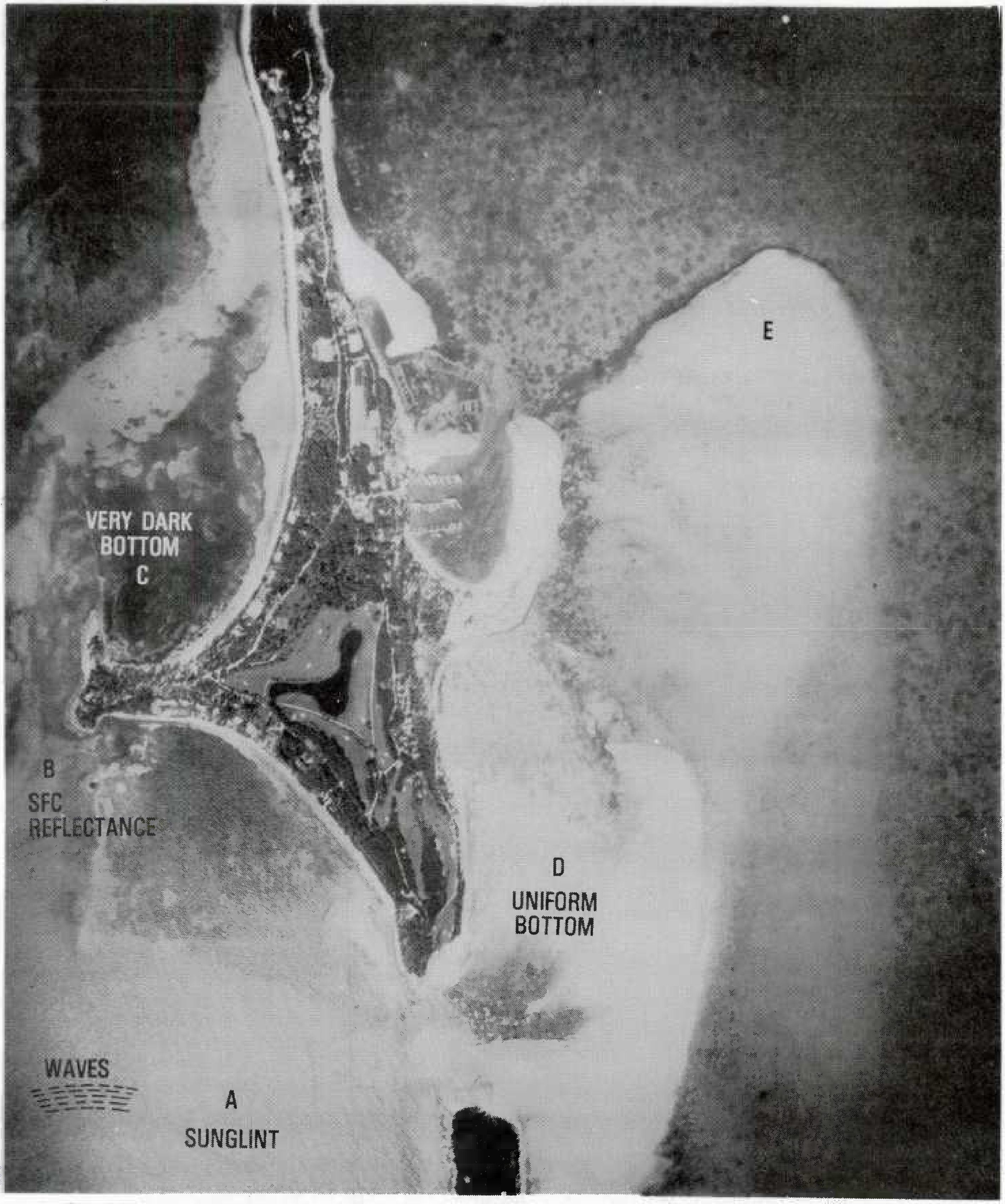

Figure 2. Cat Cay, Bahamas, July 10, 1979, color aerial photograph (1:12,000)

roughness conditions, the photographs can be highly noisy to the extent that little bottom detail can be resolved.

Cross-correlation has not been tested as to its applicability in sunglint areas. It is believed, however, that it will be necessary to avoid sunglint areas by some prescreening of the data on either the photograph or the digital data before a correation is attempted. Three types of screening might be considered: manual (human) outlining of the sunglint region; computer automated identification based on intensity characteristics (level, signature, statistics, etc.) and multispectral techniques. This prescreening could simply be human interaction that outlines the sunglint area prior to photographic digitizing such that this area is omitted. Automatic screening for sunglint avoidance might be achieved through examination of the spectral digital data. High reflectance values from the digitized red emulsion (red or IR part of spectrum, depending on film type) of the aerial photograph can signify land and vegetation or high surface reflectance. The red emulsion of IR film measures mostly surface reflectance since the red visible or near IR light has minimal penetration of the water column. Through examination of the digital values from the photographic red emulsion, screening for high surface reflectance might be adequately performed. This screening would signify that stereobathymetry cannot be done on those data points. Multispectral screening is not at all uncommon for the suppression of sunglint in aerial images: red filters are frequently used on cameras to suppress sea surface reflectance. Modification of the "red filter" techniques might also be used in an image enhancement mode to "remove" or to "see through" sea surface reflectance area. Extraction of the "red channel" information from the photograph and its combination (e.g. subtraction) with the other channel information may allow identification/removal/suppression of these surface effects.

Another approach one might explore to detect environmental surface constraints is the use of Fourier analysis (as suggested by J. Hammack, DMAHTC). As indicated, surface reflectance effects are associated with wave action. In some cases the spatial patterns of surface disturbances should be detectable with appropriate spectral analysis techniques. Other pattern analysis/recognition methods could also be applied to this problem to identify/classify these surface reflectance problems.

## B. WATER OPTICAL PROPERTIES/TURBIDITY

A difficult problem for determining depth from stereophotography results when the water optical properties are too turbid to allow detection of the bottom features. In many instances the photo interpreter is unsure as to whether the bottom or highly turbid water is being observed. An example is illustrated in Figures 3 and 4. Figure 3 is a color aerial photograph of the offshore cays off Cedar Keys, Florida. Notice in Figure 3 the long, streaming patterns between the offshore islands. The patterns,

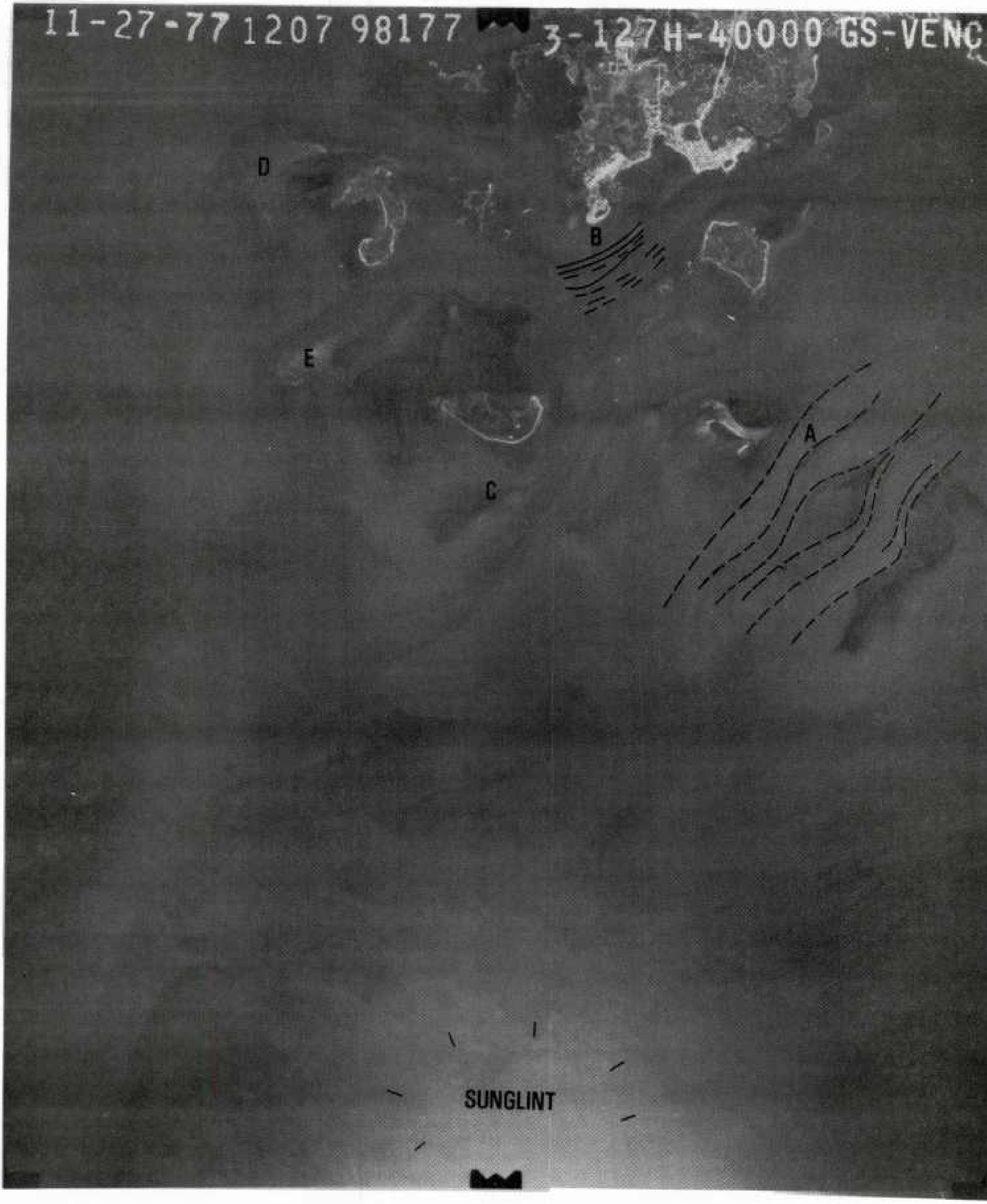


Figure 3. Cedar Keys, Florida, Nov. 27, 1977, black and white aerial photograph (1:80,000)

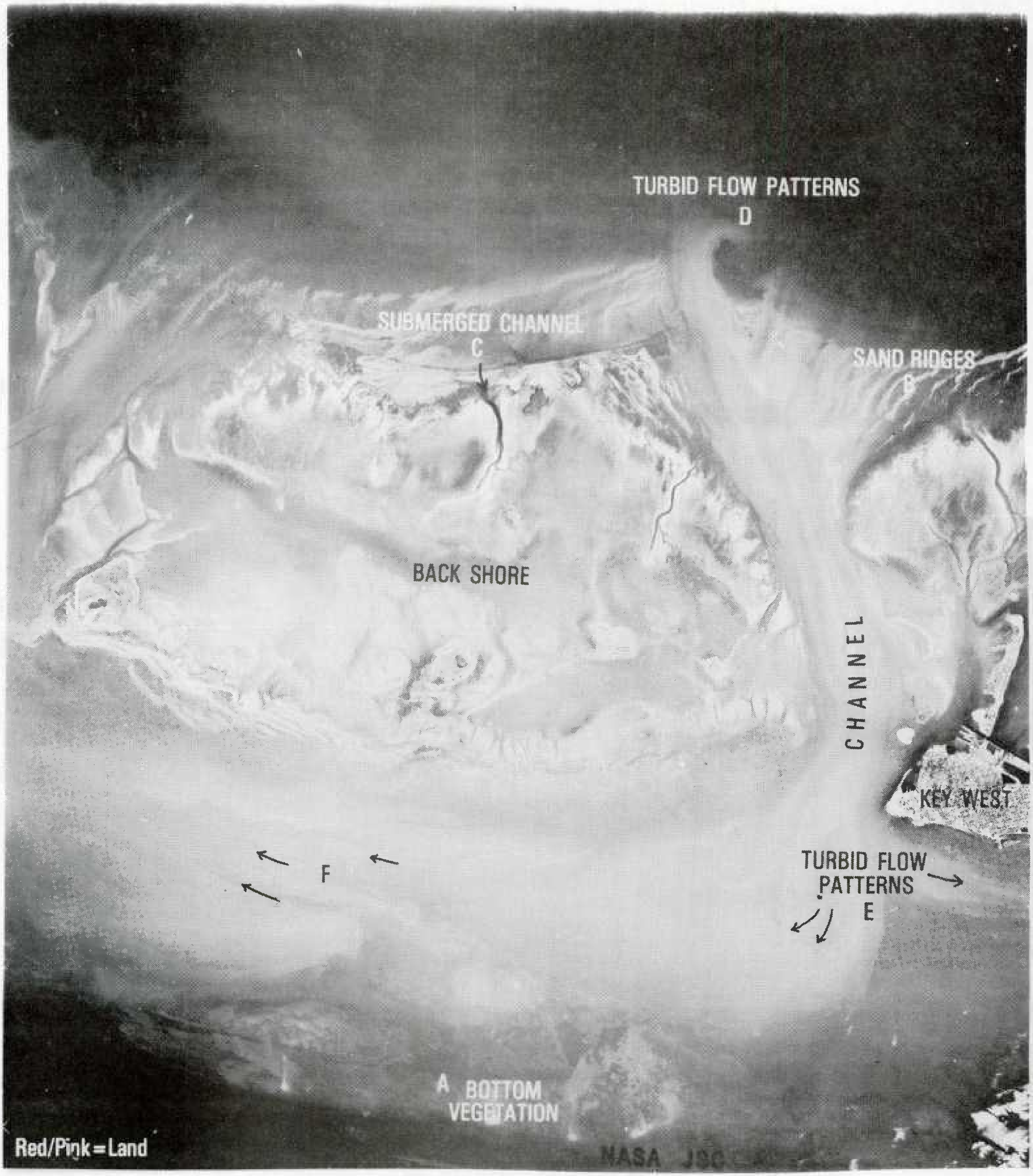


Figure 4. Key West, Florida, Oct. 15, 1979, color IR aerial photograph (1:122,000)

which turbid water develops as it flows with the dominant surface currents, are keys to the interpreter that this is turbid water and not bottom features. These flow patterns are observed throughout Figure 3, in particular, at Annotations A and B. Annotations C, D, and E illustrate shoal areas in which stereobathymetry could be used. These regions are distinguishable as being more stable, brighter areas and do not have the similar flowing features. Figure 4 is a color infrared photograph of the Key West, Florida, area. Many of the bottom features are recognizable within the photograph (see Annotations A, B, C); however, there are several areas where flow patterns within the water column indicate that turbid water obscures the bottom. These patterns are annotated as D, E, and F. The location of these patterns is within the channels where high current flow would reflect the associated high turbidity located there. The water turbidity can be seen to chance drastically between the channel and the back shore; this photograph illustrates the high variability of turbidity in coastal waters.

Recognition that these areas have high turbidity and that the water depth cannot be obtained using stereobathymetry may be a difficult problem. Again, some degree of prescreening of the photography is necessary to avoid these turbid areas. Turbidity flows are presently recognized through photographic interpretation. Pattern recognition techniques can be developed for automatic identification of turbid water areas. Such schemes can be based on various classification type algorithms (statistical, shape, Fourier content, etc.).

Finally, one should estimate the extent of these water column (optical properties) problems for stereobathymetry in coastal waters. Of course, the geographical location of the coastline, near-shore circulation, and local meteorology have a direct influence on the variability of coastal optical properties. Coastal optics can be extremely variable, both spatially and temporally. The limitations of applying stereobathymetry in differing water optical property regions are not presently known. It is difficult to assess the limitations for the stereobathymetry techniques, since they are also dependent on bottom contrast, type, and surface reflectance. In general, as the water turbidity increases, the depth to which stereobathymetry can be used decreases. The operational depth for stereobathymetry in (1) clear waters such as in the Bahamas ($\alpha = 0.2$) is about 8 meters, (2) in semiturbid waters such as; e.g., in a clear estuary ($\alpha = 1.2$) is about 3 meters, and (3) in turbid coastal waters ($\alpha = 2.0$) is about 1 meter. (Many papers have been written on the penetration depth of sunlight into the ocean dependent on the optical properties, e.g., Clark, 1937; Rampa, 1961; Oster, 1935).

## C. BOTTOM REFLECTIVITY/BOTTOM TYPE

The type of bottom in the stereoimagery is influential in defining the detail and accuracy to which the water depth can be calculated. Extremely dark bottoms of clay/silt or dense vegetation have a reflectivity of about 2%. Thus, the intensity of the return light is quite suppressed as opposed to a light, highly reflective (10%), white sand bottom (Lyzenga, 1979). It is evident that visible light from deeper water can be photographed over highly reflective bottom materials. In many cases, however, it is difficult to assess whether the bottom type is dark or if the water is indeed deep. Figure 2 illustrates such a very dark bottom at Annotation C. In this area, even humans using stereoplotters have difficulty in determining the degree of parallax or water depth.

In addition to the dark bottom issue, another problem occurs in homogeneous areas with high bottom reflectance. Because geometric depth extraction techniques depend on knowing common points in both stereopairs, regions around these points must contain enough information to allow automatic identification of such match points. In large, light, homogeneous bottom type areas, human operators have difficulty in identifying the match point with a conventional stereoplotter (keeping the "height-dot" on the sea floor). An example of a uniform bottom reflectance is illustrated in Figure 2 at Annotation D. In this area, the high bottom reflectance limits the use of the stereoplotter to extract water depths. In other areas within Figure 2 (see Annotation E) problems may also occur in extracting depth, since relatively little bottom contrast exists. The bottom type issue affects automated depth extraction techniques in basically the same way it affects stereoplotter operation. Humans can generally tell, however, from photo interpretation that they are in problem areas. The results of simple correlation techniques will not detect such problems and will appear to be giving proper match point identification (parallax). Both manual and automated prescreening should be considered for this problem. In addition, image enhancement techniques (e.g., to bring out contrast) can be applied to photographs to increase the performance of both human-operated stereoplotters and automated correlation algorithms. Finally, it may be possible for most of these large, homogeneous areas to interpolate depths based on a simple isodensity slicing of the digital values (see section III). In general, it will be important to determine quantitatively the relationship of bottom contrast, spectral content, bottom gradients, spacial frequency, etc., and successful correlation; likewise, quantitative relationships for depth and density need to be explored/extended.

## D. CLOUD SHADOWS

In attempting to outline the environmental constraints in automated stereobathymetry, the artifact of cloud shadows in the stereophotography should be considered. Figure 5 illustrates a water surface covered by numerous cloud shadows. The mottled patterns are characteristic of a relatively extensive cloud cover with the sun periodically breaking through. Other cases of cloud

Figure 5. Cat Island, Dec. 14, 1978, color aerial photograph (1:12,000)

cover may be a single, well-defined cloud shadow that appears as a dark linear feature on the water surface. The darker side of the shadow may appear to represent changing turbid water conditions, or simply deeper water. As easily surmised, the shadows add a complicating problem to depth extraction.

Relative to automated geometric depth extraction, shadows cause two problems: (1) the match point identification algorithm may "match" on the surface cloud shadow common to both images and, thus, the match point will not represent seafloor topography; (2) the cloud image may effectively reduce the (bottom) signal-to-noise ratio and, thus, make the correlation results less reliable. As with the other enviornmental constraints, prescreening or preprocessing of the photograph will be required; both human interaction and computer pattern recognition algorithms should be considered for cloud shadow detection.

# V. WPP PROGRAM PLAN, PHASE ONE

The preceding two chapters presented key issues associated with Water Penetration Photogrammetry for automated depth (bathymetric) information extraction from stereo color photography in near-shore (coastal) waters. This chapter will outline the advanced development efforts to be carried out for the remainder of the WPP Phase One effort for extension/investigation of algorithms for depth extraction and handling environmental constraints. DMA has funded this Phase One work at a two man-year level during FY83-84. Phase Two engineering issues are presented briefly in the next chapter; these issues are included here as background information for DMA planning of the outyears for the WPP Subtask.

NORDA Code 371 (Pattern Analysis Branch) will continue its evaluation and extension of automatic match point algorithms and environmental constraint removal algorithms during FY83-84. These investigations will deal with the key issues outlined in Chapters III and IV. Prime emphasis will be placed on softcopy procedures compatible with DMA's emphasis on such all-digital approaches. In particular, the two major aspects of Phase One of this project are (1) the development of a WPP testbed and (2) the conduct of a comprehensive experimental/development program.

The WPP testbed capability will provide the vehicle for extensive experiments and will consist of several elements.

(a) Photographic dataset with associated ground (sea floor) truth and control information received from DMA.

(b) A collection of stereo/geometric (match point) algorithms.

(c) A library of appropriate image enhancement routines.

(d) A collection of pattern analysis algorithms

- for identification of environmental conditions.
- for potential use in a symbolic scene content approach to stereo/geometry.

(e) Analog stereo compilation equipment (Wild B-8).

(f) Softcopy (digital) stereoimage display capability.

Each of these items is briefly discussed in the following paragraphs.

(a) Initial photographs received from DMA have been used in the preliminary trials noted in Chapter III. A complete analysis of the attributes of the photography required to support this WPP is being made. This study will address the range and availability of control, ground truth, photographic overlap, and the variety of sea floor and environmental conditions. It will also consider the possibility of computer-generated (synthetic) or computer-modified imagery for test cases to use in controlled match point algorithm experiments involving known/precise radiometric/geometric patterns.

(b) As mentioned in Chapter III, NORDA has briefly reviewed three automated correlation systems. The most transportable of these is the all-software approach called DIMP (Norvelle, 1981). These algorithms are currently being installed at NORDA. This algorithm holds the most promise for the WPP task. Software simulations of the other two algorithms (ACE and Gestalt Photomapper) are being considered. Other examples in the literature are also being investigated for potential incorporation in the WPP Testbed.

(c) A number of enhancement routines are already resident on NORDA computers. These libraries, along with those at DMA, NASA, and other institutions, will be reviewed for their application to the WPP enhancement problem. Appropriate routines will be installed at NORDA's Pattern Analysis Laboratory and integrated into the WPP Testbed.

(d) The later stages of Phase One will investigate pattern analysis/recognition approaches for scene content identification, e.g., for application in detecting environmental problem areas. NORDA Code 371 is involved in a number of projects that require such techniques: shape measurement, edge detection, statistical pattern identification/classification, etc. Where appropriate, these routines will be extended/developed to apply specifically to the WPP pattern recognition problem. Other routines will be imported as necessary.

(e) Items (e) and (f), stereocompilation/display equipment, will be used to generate photo interpretation check cases for comparison with the automated depth determination and for evaluation of image enhancement techniques. These hardware items are part of NORDA's in-house commitment to instrumentation/computer facilities for MC&G in the Pattern Analysis Branch. In particular, new digital image display hardware is being procured to be compatible with the DMA Remote Work Processing Facility (RWPF).

In addition to the WPP Testbed development, NORDA has outlined the following experimental activities for the WPP Phase One.

(a) Correlation hardware/software techniques have been studied at considerable length, as indicated in the literature search in Chapter VII. Areas extensively covered in the literature have been speed, special hardware, and topographic use for automated correlation. Therefore, the development of "new" correlation techniques is not intended under this WPP Subtask. Efforts will be required, however, to evaluate existing techniques and to extend them to color shallow-water photography; specific issues to be examined were listed in Chapter III, Automated Depth Extraction. A key issue in this regard is the exploration of the color information in the photography and automatic measures of reliability.

(b) One key issue in evaluating/extending stereo/geometric and density interpolation techniques is knowledge of "true values" for test and calibration. For the investigations on correlation algorithms, one must know actual pairs of match points. These can be obtained from ground (sea floor) truth supporting the photographic imagery and from human measurement (determination) of the points through the use of stereoplotters. DMA has obtained extensive calibration/ground truth data over its photobathymetric test range in the Bahamas. This information can be used to support image test sets for this area. NORDA will use its own stereo equipment for man-in-the-loop studies and manual match point determinations. Also, preliminary discussions have been held relative to the use of higher precision instruments at DMA, NOS, and other agencies to obtain the necessary "true" match point data. True bathymetric information is needed to evaluate the density techniques. A similar set of calibration data based on the above sources will be used for these studies.

(c) Development of the necessary test imagery is an important part of this Subtask. These controlled datasets are required for reliability and accuracy experiments. This database must also contain adequate variability of seafloor and environmental conditions (e.g., bottom reflectance/patterns, photographic overlap, sun angles, surface/wave conditions, water optical properties, etc.). It is anticipated that some of the database test imagery may result from specific digital modification of DMA stereophotographs (e.g., known additive noise, blurring, etc.) and from synthetic scenes generated to have precise properties. Using this variety of known imagery, experiments can be performed to determine the photometric characteristics upon which automated depth extraction depends. Such <u>controlled investigations/tests for correlation dependence</u> have not been found in the literature; they will play an important role in the WPP development effort.

(d) As indicated in Chapter III, reliability of correlation is a key issue since correlation procedures are not fail-safe, i.e., undetected false match points can be generated that will result in erroneous depth "soundings"; this situation is critical for the bathymetric charting problem. Therefore, specific investigations will be directed at developing automatic "quality assurance" procedures. For example, multiple correlations based on different stereo pairs, color channels, etc., can be used to verify a match point determination (if the computation load can be handled). Such techniques can also be combined with accuracy improvement procedures.

(e) Image enhancement experiments will be performed; trade-offs between the complexity of match point algorithms and such preprocessing will be investigated. For example, band ratioing, spectral and spatial filtering, and intensity equalization algorithms will be studied. As a secondary benefit, such digitally enhanced photographs will be used in a limited set of experiments with photo interpreters.

(f) The last key issue in the WPP Subtask is the identification and evaluation of techniques to handle the environmental constraint problem. Priority will be given to investigating the effectiveness, relative to match point determination, of manual and semi-automated prescreening.

The two-year WPP development effort (Phase One) outlined above will be documented through appropriate NORDA Technical Notes and Reports. A comprehensive plan for the conduct of Phase Two of the WPP Subtask will also be prepared. Furthermore, under Phase Two of this project, algorithms/testbed software will be transferred to DMA (where possible) through the compatibility of the Pattern Analysis Laboratory hardware/software and DMA image processing facilities. This interaction will form the basis for completion of Phase Two. This second phase of the WPP Subtask will be involved with an end-to-end engineering design to incorporate the advanced development results of Phase One and to provide DMA with a complete Water Penetration Photogrammetry System.

## VI. PHASE TWO: SYSTEM ENGINEERING INVESTIGATION, A TOTAL SYSTEM

The Phase One advanced development effort described in the previous section will establish prototype algorithms for the automation of depth determination and the handling of environmental image constraint/problems using color stereophotography for near-shore (coastal) bathymetry. After this two-year effort, a complete engineering design and development of a total Water Penetration Photogrammetry System will receive specific attention. The review/analysis to date suggests that the following topics need to be addressed during this Phase Two effort.

A. Determine the optimal solar altitude, incidence look angle, and azimuth look angle for achieving maximum illumination of the sea bottom, maximum image contrast, and minimal specular reflectance for photogrammetric bathymetry. It is interesting to note that the first research priority for photogrammetric bathymetry was identified 20 years ago by Solodovnikova (1962) as the determination of optimum conditions for taking aerial photographs for underwater surveying, which are primarily dependent on the light regime. If the open literature is a true indicator, this research has not yet been completed; therefore, research in this area should be pursued. While a determination of the optimum photo acquisition parameters would have no bearing on the problem of mapping from existing photography, this determination will be very important for future mission planning.

B. Initiate an investigation to optimize future data acquisition for the two-media photogrammetry problem. The best reference system appears to be the Canadian Hydrographic Service's "aerial hydrography/laser bathymetry system" (MacPhee et al., 1981; Masry and McRitchie, 1982). The airborne component of the system includes aerial survey cameras (loaded with color film and black-and-white infrared film), laser bathymeter, and navigation and positioning sensors. If digital stereomapping is to be a significant future method of determining near-shore bathymetry, a single camera with color infrared film (green, red, and infrared sensitive) or an as-yet undeveloped film with blue, green, and infrared sensitivities might be used. Also, film calibration should be obtained in the future so that a radiometric correction of digital data can be performed. The rapidly growing technology of solid-state scanners with on-line multispectral digitization will eventually be realized in airborne digital photogrammetric data acquisition system, eliminating the film problem.

C. Inventory archived film and associated control to determine:

- Date, time, and place of photography.
- Nominal flying height, photo scale, overlap.

- Calibration film wedge: present/absent.

- Camera calibration records.

- Number of photographs in blocks.

- Ship hydrographic information.

- Usefulness of existing photography for stereocompilationon basis of problems: sun reflection, cloud reflection, artifacts, turbidity and visibility of sea bottom, water surface condition, percentage of usable coverage in photo blocks and models.

- Status of control (including depth at time of photography) and tidal datum for sites, as well as likelihood of obtaining additional control by ground survey, i.e., site accessibility.

- Difficulty of performing aerotriangulation and, in particular, analytical aerotriangulation.

- Rank from easy to difficult for analog, analytical, and digital compilation.

D. Determine processing problems and requirements for an operational digital mapping system. Some of the areas needing investigation/experimentation are the following:

- Infrared provides the best definition of the water-land interface for aerotriangulation/leveling of models. Since the Navy has used color film only, investigate the use of the red band as an aid to aerotriangulation.

- Investigate image shaping and prediction algorithms that account for the failure of match points to lie on epipolar lines. Investigate the computational impact imposed when film is scanned on a drum type microdensitometer; i.e., when scanning is not performed along epipolar lines. The latter investigation can be considered a component of the systems analysis, which will determine the scanning technology to be used in a production system.

- Investigate the applicability of correlating red band with green/blue band on a pixel-by-pixel basis to "strip" the water column. This technique has been successfully applied in MSS bathymetry experiments (Cooper, 1982). This within-image correlation (to differentiate it from within-stereopair correlation for computing bottom feature elevation) may reduce the computational load, if properly combined with geometric depth techniques; therefore, a "parallel" correlation scheme might be an optimum scheme. This issue should be addressed at the system analysis level.

- Investigate the applicability of scattering models of the atmosphere to cloud correction.

- Perhaps the most difficult problem to solve is how to enhance/discriminate bottom features in turbid imagery and how to derive a depth-variant index of the bottom type from the resulting features. An algorithm developed by Lyzenga (1981) to solve the latter problem using aircraft MSS data is potentially useful.

- The trade-offs between the computational load encumbered by preprocessing and the benefits of reduced computation in correlation and improvement in reliability and accuracy need to be evaluated.

- Investigate interactive editing techniques which can be used when the automated depth extraction algorithms flag a region as not processable.

E. Initiate systems analysis of instrumentation and software/firmware for an automated digital stereomapping system. The primary instrumentation concerns are the choice of scanning technology for analog-to-digital conversion of photography and computer facilities for image preprocessing, correlation, and depth determination. It is believed that existing hardware (computers, densitometers, and graphics terminals) are commercially available, but the most appropriate hardware/software combination would have to be investigated. The choice between an off-line and on-line system will have significant impact on the system configuration because of the requirements for man-machine interaction (for quality checking). This investigation will include an analysis of computational load and software/hardware tradeoffs. It will also consider NAVOCEANO data acquisition and DMA Production Center requirements and constraints.

## VII. REFERENCES

SUBJECT CATEGORIES:

(1) Control
(2) Film/Photography
(3) Aerotriangulation
(4) Instrumentation/Automation
(5) Geometric Correction
(6) Radiometric Correction
(7) Preprocessing
(8) Compilation/Correlation
(9) Accuracy
(10) Post-correlation: Interpolation/DTM
(11) Costs
(12) Multi-spectral Bathymetry
(13) Pattern Analysis


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## APPENDIX A

## FILM/PHOTOGRAPHY INVESTIGATIONS

Helgeson (1970) suggested that efforts to increase water depth penetration and improve the recording of bottom detail by eliminating the blue-sensitive, yellow dye-forming layer in color film (e.g., Current, 1969; Willard, 1969) or the use of a yellow filter (Wratten No. 12) (e.g., Lepley, 1968) are incorrect procedures because the yellow-forming, blue-sensitive layer extends into the water transmission band, as does the short wavelength sensitivity of the green-sensitive layer. Rather than eliminating the blue-sensitive or yellow-forming layer, Helgeson suggested that relocating its peak sensitivity would be more beneficial, and the red-sensitive layer could be eliminated. While Helgeson did not identify an optimal bicolor film, he did state that "in terms of providing the most efficient use of the energy that is likely to be present in a water-depth or distance penetration problem, the most reasonable approach is to use a sensor that responds in the area in which the media will most probably transmit, and to record as little of the scattered light as possible."

Specht et al. (1973) designed an experimental film for the specific purpose of providing maximum information about underwater detail and water characteristics from aerial photographs. The work of Helgeson (1970), Ross (1969), Helgeson and Ross (1973) and other investigators led Specht to conclude that a color film designed for oceanographic applications should have sensitivity in both the blue and green spectral regions with no red sensitivity. Specht and earlier investigators determined that the red-sensitive film layer provides information chiefly about surface objects and the sea state and records specular reflections to a greater degree than the other layers. The experimental two-layer film had peak sensitivity at about 480 nm for maximum penetration in ocean waters and at 550 nm for maximum penetration in bay waters. The shift of bay water toward longer wavelengths is attributed to yellow organic matter and various particulate matter. The dyes formed in the two layers were the complementary colors, magenta and green. These two colors were chosen because they provide maximum visual discrimination of color differences. The ability of the film to record underwater detail was reported to be superior to that of either regular color film or film in which the blue-sensitive layer was omitted; the specular reflection from the water was less noticeable. No decision had been made by the Eastman Kodak Company at the time of publication to make the film commercially available--a list of available color aerial photographic materials was published by Fritz (1976).

Boller and McBride (1974) examined the available data on the spectral transmittance of water and the spectral irradiance of daylight-penetrating water to various depths, and concluded that the maximum spectral transmittance of water occurs near 500 nm or in the blue-green region of the spectrum. Therefore, the light reaching any underwater scene is largely blue-green in nature corresponding to the transmission window. On the basis of this conclusion an experimental black-and-white film for underwater photography was developed. Two improvements are claimed for this film: improved spectral sensitization and higher-than-normal contrast. The drop in spectral sensitivity of general-purpose panchromatic films at 500 nm was judged to come at exactly the wrong place for maximum efficiency in water-penetration applications. Accordingly, a sensitizer was chosen that provided relatively uniform sensitivity across the blue-green region of the spectrum and cut off at about 530 nm. The red sensitivity was eliminated to improve water penetration. During aerial tests a Kodak Wratten Filter No. 3 was used to provide a narrow band-pass corresponding to the downwelling irradiance through water. "Because light scattering reduces image contrast, an improved emulsion was designed which produces a higher contrast than is normally associated with films in this speed range." The experimental film reportedly showed improved image contrast and enhanced underwater detail when compared to general purpose panchromatic films in aerial tests. As in the case of Specht's experimental film, the Eastman Kodak Company had not made a decision to manufacture the experimental film as of the date of publication.

A number of investigators have evaluated the effectiveness of available aerial films in "seeing through" water (e.g., Rudder and Berry, 1972; Lockwood et al., 1974; Sunamura and Horikawa, 1978). The purpose of these investigations has been the determination of the most efficient film-filter combination(s) to be used for water depth penetration and for recording the sea bottom.

Rudder and Berry (1972) investigated the effectiveness of several films in "seeing through" turbid water and recording the bottom with adequate contrast. The film choice was determined to be dependent upon several factors: the aerial exposure index (AEI), the spectral sensitivity of the film, ambient light conditions, and water turbidity. These factors are interrelated, but the key parameter was determined to be the AEI. The film speed, as determined by the AEI, establishes the length of time required to expose the film for a given ambient light level, which is affected by prevailing atmospheric conditions (cloud cover, haze, fog, etc.) and the optical transmissivity or turbidity of the water. These attenuating parameters contribute to the spectral sensitivity requirements of the film. To have sufficient sunlight illuminating underwater terrain and yet not have specular reflections from the water's surface obscuring the area, it was determined that the solar angle should be between 15° and 32°. (Keller (1977) identifies the optimum solar angle as being between 20° and 25°.

Vary (1968) identifies the optimum angle as being between 26° and 34°.) This constraint restricts aerial beach reconnaissance photography to only a portion of the morning and afternoon on a clear day. The use of higher speed films was shown to permit aerial photography at lower solar angles. It was concluded that false color infrared films (Kodak 2443 and GAF 2575) significantly hindered the ability of the photogrammetrist to ascertain underwater detail when the water was not reasonably clear. Color negatives could not be efficiently used for the same reason. Positive transparencies were required for efficient interpretation of the imagery. Good results were reported for film types 2445 and 2448, but relatively long exposures were required and, thus, could be used only at low aircraft velocities. Positive transparencies made from Kodak Ektachrome EF Aerographic type SO-397 color negatives provided the most utilitarian results--Specht et al. (1973) reported their experimental film to be intermediate in speed between types 2448 and SO-397. Rudder and Berry's study dealt with turbid waters. Lockwood et al. (1974) evaluated the SO-397 film over a "typical" water body.

Lockwood et al. (1974) performed an evaluation of the water depth penetration recording efficiency of nine film-filter combinations over a "typical" water body. These tests were a part of a continuing program of the Photographic Science Office of the NASA Photographic Technology Division to optimize photographic recording systems. The films tested included the experimental two-layer color film reported on by Specht (1973), a two-layer (minus blue layer) film (SO-426), a normal color film (SO-397), a panchromatic black-and-white film (2402), and a black-and-white infrared film (2424). Selective filtration was used with all films. Film type SO-397 with a Wratten No. 3 filter for haze reduction was reported to produce the best overall imagery for water depth penetration at all depths. Color contrast was reported to be excellent at all depths, and definitely superior to the other films. The water depth penetration ability of the experimental film was found to be comparable to SO-397 film, but its color contrast was not as good.

The photographic requirements for operational photogrammetric bathymetry are most clearly identified in the practices of NOS. Brewer and Heywood (1972) and Keller (1975), in reporting on mapping operations within NOS, identified the photography used in mapping coastal boundaries and bathymetry. Brewer and Heywood reported that for coastal boundary mapping, NOS obtains photographic coverage on two types of film emulsion. Black-and-white infrared film is used to capture the water-land interface at specific stages of the tide, and natural color film (film/filter combination not identified) is exposed for use in aerotriangulation and basic compilation. (Masry (1980) also reports the use of these two film types in coastal mapping.) The infrared photography is coordinated with each specific tidal datum by making the exposures when tide staffs indicate mean high water (MHW) or mean low water (MLW) level readings. In general the allowable vertical tolerance from the observed tidal datums for photography taken at MHW and mean water level (MWL) is greater than that for photography taken at MLW because of the gentler slope near the MLW. All photography of shorelines is taken with a 60% forward endlap. The scale of aerotriangulation photography and infrared photography is, in general, 1:30,000, and both types of photography are taken as near to the same date as possible. Keller (1975) states that two film types are used only when sufficient vertical control cannot be established. If adequate vertical control can be established, then natural-color film alone is used. Keller also states that "false-color infrared can be used alone to delineate shoreline where the tide range is less than the water penetrating afforded by the emulsion." In this instance, the water-land interface is determined from a black-and-white photograph sliced from the infrared photography. NOS photographic requirements for photogrammetric bathymetry are essentially the same as those for shoreline delineation. Masry and McRitchie (1980) also advocate the use of black-and-white infrared and color photography in the mapping of coastal waters.

The 1:30,000 photo scale reported by Brewer and Heywood (1972) should not be construed to be an optimal photo scale for photogrammetric bathymetry. A later article on NOS activities by Keller (1977) states that photography is now obtained at a scale of 1:20,000. Reported scales have ranged from this high value down to the 1:500 scale reported by Lundahl (1948). Harris and Umbach (1972) reported an optimum photo scale of 1:15,000 for a test site off the coast of Puerto Rico; they recommend a flying height at least 100 times as great as the depth of water to be mapped so as to minimize the errors in refraction compensated coordinates of vertical control. Assuming a camera lens with a 6 inch focal length, a maximum observable water depth of 75 feet, and a flying height of 7500 feet (75 x 100), the minimum photo scale would be 1:15,000. The scales (1:12,000 and 1:24,000) of the Navy's archived near-shore photography are consistent with reported current practice.

Reported forward endlaps (70-80%) for photography to be used in bathymetric mapping are greater than the 60% endlap used in the conventional mapping case. Rosenshein and Goodwin (1977), for example, performed stereocompilation with a 60% endlap and reported that 65-75% endlap would be preferable. Harris and Umbach (1972) specify a 70% photographic endlap and sidelap so as to optimize the balance of error residuals caused by sea surface roughness and by the effect of a smaller than normal base-to-height ratio on the geometry of block aerotriangulation and stereoscopic compilation. This greater than normal overlap was also specified so as to ensure complete stereocoverage free of obscuring sun reflection and to meet analytic aerotriangulation needs. Endlap and sidelap of DMA's archived photography is not known at this time.

APPENDIX B

# GEOMETRIC-RADIOMETRIC CORRECTION

## A. GEOMETRIC CORRECTION

An accurate solution of the aerotriangulation problem and the determination of depth curves and spot elevations requires correction of geometric errors in image point positions introduced by the imaging system and processing instrumentation, and a reduction of point positions to the photographic reference with origin at the principal point. The systematic errors in single-media photogrammetry (atmospheric refraction, earth curvature, lens distortion, film shrinkage/expansion, comparator) are well known and documented in standard texts (e.g., Wolf, 1974; ASP, 1980). The two-media photogrammetric problem must account for the additional positional error introduced by refraction at the water-air interface. The apparent depth of water as measured with a plotting instrument or as computed analytically is less than the true depth and is subject to a correction factor based on the index of refraction of the water and the angle of observation, which is a function of flying height and air base, as well as the depth of the water itself and surface condition. The geometrical properties of two-media photographs have been investigated, mainly in the case where the boundary surface is a plane, and approximate solutions for the correction of point positions obtained.

The model consists of an expression of the radial image displacement for vertical photographs with an assumption of vertical photography and a placid water surface:

$$d = \frac{Rh[1 - (1/a)]}{H - h}$$

where

d is the required correction, in meters, to be applied to the photograph image. Its sign is always negative or toward the photo center.

R is the radius of the photographic image, in meters, and is equal to

$$(x^2 + y^2)^{1/2}$$

where x and y are refined photocoordinates; i.e, corrected for systematic errors and reduced to principal point reference.

h is the depth of the underwater point with respect to the surface datum at the time of photography. It is expressed in meters and is always negative in sign.

H is the flying height, in meters, with respect to mean sea level.

a is the ratio of tangents of the angles of refraction (r) and incidence (i) (Rinner, 1969). It is dependent upon (R), (f), and (n).

$$a = \frac{\text{true depth}}{\text{apparent depth}} = \frac{\tan r}{\tan i} = [n^2 + (n^2 - 1)\tan^2 r]^{1/2}$$

where

n is the index of refraction for rays passing from water into air. Its nominal value is listed by various authors as being either 1.33 or 1.34 for sea water. More precise information is given by McNeil (1980).

f is the camera focal length in meters.

tan r is the ratio R/f for a vertical photograph.

The refraction corrected values of photo image points are obtained by:

$$x' = x[1 + (d/R)]$$
$$y' = y[1 + (d/R)]$$

The Harris and Umbach model is useful for refinement of photographic points used in aerotriangulation but not for the correction of unknown points.

Tewinkel (1963) and Meijer (1964) present a method for applying variable depth correction factors to the apparent depths measured with analog stereoplotters. The procedure requires that the apparent depths be plotted, corrected to true depths by reference to contours of constant correction factor, and contouring the resulting values using apparent depth contours as a guide. Improved values for each depth can be obtained by using the mean value of depths determined from alternate flight lines (ASP, 1975). The relationship between apparent and true depth is given by Meijer as:

$$h = Fh'$$

where

h is the true depth,
h' is the apparent or observed depth,
F is the correction factor.

Meijer's formula for fomputing the correction factor F is:

$$F = \frac{b \;/\; (H+h')}{\dfrac{x}{[(n^2-1)d_1^2 + (H+h')^2 n^2]^{1/2}} + \dfrac{b-x}{[(n^2-1)d_1^2 + (Hh+h')^2 n^2]^{1/2}}}$$

where

the origin of a horizontal coordinate system is placed at the left photo station and x is positive in the direction of flight, and y is positive in the direction normal to the direction of flight.

$H$ is the flight height
$h'$ is the apparent depth
$b$ is the base
$n$ is the index of refraction
$d_1 = (x^2 + y^2)^{1/2}$
$d_2 = [(b-x)^2 + y^2]^{1/2}$

This formulation does not, as noted by van Wijk (1964), account for point displacement, which results from the fact that, generally, two corresponding light rays do not intersect after refraction. Except in special cases, the rays are not coplanar and match points do not lie along epipolar lines.

Slama (1977) raised three objections to the procedures by which true depths are determined with analog stereoplotters: time-consuming hand computation and manual intervention by the plotter operator; only an approximation is obtained, in that a best-fitting graphic for a model is developed from an average algorithm from which correction factors are then interpreted; and corrections for positional errors are not made. These objections were overcome by interfacing a digital output with an analog plotter so that instrument coordinates (x and y) of points and apparent depths could be fed to a computer and corrected for the effect of refraction at the water-air interface. Slama noted "that the apparent rays do not intersect at a point; however, the operator sets the floating mark so that he views zero x-parallax while having a separation of the measuring mark in the y-direction..." Y-coordinates were assumed midway in this separation. The latter assumption can be easily enforced in an analytical digital system, but since x-parallax is determined by the correlation points in such a system, the x-coordinates to be used in space intersection must be position-corrected correlation points. Rinner's (1969) expression for the ratio of true and apparent depths and the geometry of intersection of a pair of rays from an underwater object point were used by Slama to derive corrections equations. This effort of Slama's was an attempt to at least partially automate photogrammetric bathymetry. The corrective equations have probably since been modified and incorporated in the NOSAP analytical plotter system about which Slama (1980) has since reported.

Slama's correction for apparent to true depth is:

$$h = \frac{h'}{\dfrac{1}{a} + \dfrac{\tan r_2}{\tan r_1 + \tan r_2}\,(1/a_2 - 1/a_1)}$$

where the notation is as given in previous formulas. Slama's corrections of x and y coordinates are not repeated here.

Two iterative approaches to refraction calculation are given by Masry (1970, 1980). They are not repeated here. The procedure given in Masry (1970) has been programmed and tested in real-time on an analytical plotter (Masry, 1975).

All the procedures reviewed here are based on the assumption that the water surface is a plane. Very little analysis of the photogrammetric influence of sea waves has been done. Masry and McRitchie (1980) have investigated the practical characteristics of photogrammetric bathymetry and provide an incomplete consideration of the actual water surface in refraction calculations, but a practical correction method is not discussed. A more complete treatment of wave considerations is given by Okamoto (1982). Okamoto describes the general refraction calculation for underwater points, presents approximate estimates of the errors for any various types of waves, and techniques for correcting these approximate errors.

B. RADIOMETRIC CORRECTION

The need for radiometric corrections have been well known for a number of years (Evans, 1948). Essentially, the need arises because there is a highly nonlinear relationship between the amount of radiation incident on the unexposed film and the amount of dye produced after the film has been developed. Thus, some sort of calibration must be put on the film before processing to allow the user to determine this relationship.

Calibrations on film must be put on the film before it is developed. The calibration consists of allowing differing known amounts of radiation to expose the film. After development the film density at these points are measured (Scarpace, 1978). A phenomenological relationship is then derived between the measured film density and the log of the exposure (ergs/cm*cm). On color films, it is somewhat more complicated. Before the relationship is derived, the film density must be converted to analytical density (Scarpace, 1978). Then the relationship between analytical density and log exposure is found. This allows the user to derive radiometric values from a film density measurement. From these radiometric values, systematic errors such as lens fall-off can be corrected.

Lens Fall-Off: It is well known (ASP, 1975) that there are a number of systematic radiometric biases to photographic imagery. The largest problem is associated with nonuniform radiation in the film plane. The exposure due to a source of radiation imaged at the edges of the photograph will be less than that for the same source imaged in the center of the frame. For a pinhole camera, the radiation at any radial distance r is related to the exposure which would have been measured at the center by:

$$Eo = Er [ f / (r2 + f2 ]^4$$

where

- Eo is the exposure at the center of the frame,
- Er is the exposure at any radial distance r from the center, and
- f is the focal length or distance between the image plane and the pinhole.

For any real camera, the lens fall-off is usually a function of F-number and cosine of theta (theta is the arctan(r/f) ). In addition, most mapping cameras use an antivignetting filter, which takes out some (but not all) of the radiometric effect. Techniques have been developed for correcting for lens fall-off in multi-emulsion imagery (Kalman and Scarpace, 1979). This is particularly important in any correlation algorithm which depends on the color of the target. The relationship may be different between exposure and dye density for each of the layers on a color film. Targets with the same color may appear as differing colors on the developed film if they are imaged at different places on the film.

On color films, there are three independent dye layers. There is a different relationship between exposure (ergs/cm$^2$) and each of the dye layers. A uniform shift in exposure due to lens fall-off within a frame of small changes in exposure time between frames will cause not only a different intensity or perceived brightness on the film, but also a color shift. Also, variations in upwelling radiance with azimuth as well as variations in topography that give rise to variations in the irradiance level on the ground and, consequently, the radiance of the feature, may prevent accurate image correlation. We believe these effects must be corrected for by preprocessing the imagery before correlation (see Section V).

Slater (1980) presents a treatment of image-ratioing procedures for radiometric correction or normalization of spectral signatures. Atmospheric effects are not corrected in an absolute sense. They are simply eliminated from computations by which the normalized spectral signatures are determined by different ratioing techniques that use sums, differences, or products of multi-spectral bands.

## APPENDIX C

## MATCH POINTS FINDING SCHEME VIA CORRELATION

Norvelle's (1981) approach to automatic compilation of elevation data is based on a correlation algorithm. Given the interior and exterior orientation data and the calibration data for a stereoscopic pair of photographs, only the corresponding X and Y photocoordinates of an image on the stereoscopic pair are needed to compute its ground position. The digital correlation algorithm described here is used to obtain the necessary corresponding photocoordinates.

In this scheme, a window of gray shade values centered around the point in question on the left photograph is compared at every possible position within a specified search area to the gray shades on the right photograph. The position within the search area where the maximum correlation occurs will define, to a pixel precision, the location on the right photograph of the corresponding image. A curve is fitted in both the X and Y directions to the maximum correlation value with ones on each side, and it is then analyzed to determine to a fraction of a pixel where the peak occurs. The specified pixel coordinates of the image on the left photograph and the computed pixel position on the right photograph can be transformed off-line to actual photocoordinates and subsequently used to compute X-, Y-, and Z-ground coordinates.

The algorithm uses the linear correlation coefficient (RXY), the covariance correlation coefficient (SXY), or the absolute difference coefficient (DXY) to determine the degree of correlation between the window and the search area. The three coefficients are computed as follows:

$$RXY = \frac{\sigma xy}{\sigma x \sigma y} = \frac{\Sigma(X - \overline{X})\ (Y - \overline{Y})}{\sqrt{\Sigma(X - \overline{X})^2} \cdot \sqrt{\Sigma(Y - \overline{Y})^2}}$$

$$SXY = \sigma xt - \frac{1}{N}\, \Sigma(X - \overline{X})\ (Y - \overline{Y})$$

$$DXY = \frac{1}{N}\, \Sigma \left|\ (X - \overline{X}) - (Y - \overline{Y})\ \right|$$

where

X,Y = the gray shade values for the window and search area,

$\overline{X}$ $\overline{Y}$ = the average X and Y,

N = number of elements in the window.

The differences between the gray shades and the mean ($X - \overline{X}$, $Y - \overline{Y}$) are used in the computations rather than the absolute values (X, Y) to negate the influence of brightness differences between the images. The SXY and DXY values are still influenced by contrast differences, but RXY is not. The RXY coefficient is normalized and will always take on an absolute value ranging between 0 and 1, but XSY and DXY values will vary in range. It is important to note that in cases whereby X and Y images have constant gray levels (such as a lake, snow, etc.), the RXY and SXY will indicate poor correlation results, since their values will be very small if not indeterminate. On the other hand, DXY will give a zero value, which indicates a high degree of correlation. In the case of adverse areas, then DXY can be misleading in the absence of other correlation measures, such as the sharpness of the correlation curve.

The primary advantage of using SXY or DXY is that they require fewer computations and therefore are faster and cheaper to use than RXY. This is due to the need with RXY to compute standard deviations, $\sigma_x$ and $\sigma_y$, which are not used with SXY and DXY. For a given correlation computation, $\sigma_x$ is computed only once for the window, whereas $\sigma_y$ is computed for the search area numerous times. For example, a 15 x 15 pixel window can be correlated in 21 different positions within a 17 x 21 pixel search area; therefore, a $\sigma_y$ would be computed for twenty-one 15 x 15 pixel subsets taken from the search area. In an attempt to normalize somewhat the value of SXY, the covariance $\sigma_{xy}$ was divided by $\sigma_x 2$ (in some tests) in order to keep SXY approximately between 0 and 1. Note that in the ideal case, $\sigma_x 2 = \sigma_x \sigma_y$; therefore, the modified SXY computation becomes identical to RXY. Although this technique helped control the size of SXY, the range still varied widely in the presence of contrast differences. Because the RXY value is more consistent and predictable, it was used almost exclusively in the DIMP, even though it takes longer and costs more to compute it.

The success of the scheme depends largely on how accurately the match point location on the right photograph can be predicted. The correlation process is, after all, a local refinement to an estimated location and not a global search operation.

The quality of correlation is judged good or bad, based on the magnitude of the computed correlation coefficient and also on the magnitude of correction the correlation process makes to the predicted* location of the match point. The terms "good" and "bad" are used here to indicate conformance to statistical tests and not as an absolute measure of quality. The larger values of RXY and SXY and the smaller value of DXY indicate the higher degree of correlation.

Determining proper sizes for the window/search areas and the threshold for RXY is expected to be image-dependent. Bathymetric imagery may also require an array of thresholds (per image) or an adaptive approach in order to accommodate spatial variance due to localized environmental constraints.

*A predicted location is a computed coordinate pair after performing linear transformation (goemetric shaping) of window pixels to compensate for the difference in perspectives of the pair.

# APPENDIX D

## SPATIAL TRANSFORMATIONS

Two computational algorithms to perform spatial convolution (for features enhancement and global filtering) and space-variant contrast stretch (for homogeneous bottom details enhancement) are briefly described here. The first algorithm follows:

$$O(x,y) = \sum_{-\frac{m}{2}}^{\frac{m}{2}} \sum_{-\frac{n}{2}}^{\frac{n}{2}} p(x+i, Y+j) * C(i,j)$$

where

p(x,y) is the raw image pixel level at location (x,y),

O(x,y) is the new pixel level, and

C is the convolver (an mxn kernel).

The convolution coefficients $[c_{i,j}]$ may be selected to implement any spatial filter.

To perform local "adaptive enhancement, an algorithm based on modifying local statistics to stretch (or compress) contrast takes the following form:

$$O(x,y) = \frac{\sigma_0}{\sigma p+M/_0} * [(p(x,y)-m_p) + S*m_0 + (1-5) * m_p]$$

where

p(x,y) is the raw image pixel level at (x,y),

O(x,y) is the output (normalized pixel intensity,

p is the local standard deviation,

$_0$ is the "desired" standard deviation in the output image,

$m_p$ and $m_0$ are the corresponding local means,

M is the maximum gain, and

S is a gray level "shift" parameter.

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